1976-12

Biofeedback related to enhancement of preferred frequencies in the electroencephalogram

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BIOFEEDBACK RELATED TO ENHANCEMENT OF PREFERRED FREQUENCIES IN THE ELECTROENCEPHALOGRAM

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THESIS

BIOFEEDBACK RELATED TO
ENHANCEMENT OF PREFERRED FREQUENCIES
IN THE ELECTROENCEPHALOGRAM

by

James Lenus McClane

December 1976

Thesis Advisor: G. Marmont

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Biofeedback Related to Enhancement of Preferred Frequencies in the Electroencephalogram		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; December 1976
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) James Lenus McClane		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE December 1976
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Biofeedback
Electroencephalogram
"preferred frequency"
EEG
tegulometric frequency analysis

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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(20. ABSTRACT Continued)

Data are presented supporting the concept of a task related "preferred frequency" pattern for the experimental tasked activity.

Biofeedback Related to
Enhancement of Preferred Frequencies
in the Electroencephalogram

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1976

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A physiological basis for the term "preferred frequency" is presented. Computer modeling schemes are shown to be useful in the conceptualization of neural circuits. The Bioengineering Laboratory effort in EEG work at the Naval Postgraduate School is described. A method is developed for the investigation and analysis of "preferred frequency" patterns resulting from a pseudo-random tasked activity. Data are presented supporting the concept of a task related "preferred frequency" pattern for the experimental tasked activity.

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ACKNOWLEDGEMENT

It gives me a great deal of pleasure to acknowledge those individuals and organizations without whom this project would not have been possible.

Professor George Marmont has been of invaluable assistance as teacher, friend and advisor during the course of this work. The project is a team effort and would not progress without the assistance of the other students. LCDR K. A. Tobin, LCDR J. Fricke, LT B. Cornett, LT D. Lashbrook and LT A. R. Boutz provided many hours of support.

The Naval Electronics Systems Command supported earlier phases of the EEG work at the Naval Postgraduate School Bioengineering Laboratory.

I would like to take this opportunity to thank my wife Carol for the absolutely essential support and understanding which she provided during some of the darker moments of this undertaking.

I. INTRODUCTION

A. THE BIOENGINEERING PROGRAM

The Bioengineering Laboratory team at the Naval Postgraduate School has been engaged in intensive investigations of the human electroencephalogram (EEG) for the past several years. These efforts are directed primarily to establishing a relationship between certain frequencies in the EEG and subject activities recorded during reproducible experimental runs. The project is a complex one involving state of the art technology and the cumulative efforts of many persons. Background study for students who become involved with this work is accomplished through selection of the Bioengineering course options. These courses enable the technically based student to acquire the inter-disciplinary knowledge utilized in the research effort. The bioengineering program provides engineers with the opportunity to apply formal training to perplexing questions concerning man and his perceptions of himself.

A vast amount of information has been gathered on the central nervous system, but the subtle questions of how? and why? at localized sites of activity remain largely a matter of conjecture unsupported by experimental results. The literature available on the subject is devoted primarily to model construction and attempted analysis of raw EEG data. The individuals who specialize in this work view the

unanswered questions about the human brain as one of the true frontiers left for scientific exploration.

We are presently capable of accumulating much more data than can be translated into useful information. The human EEG, as derived from scalp mounted electrodes, contains a vast amount of information on performance, alertness, pathology and even mental or emotional well being. The approach in use by team members is fundamentally based in the belief that the information is there; it is a matter of translation for understanding.

The benefits of functional understanding of the human brain would be tremendous and the implications would be far reaching. Ultimately, the discussion involves enhancement of man's perception of himself. The human brain remains the one thing known of in the universe that has the potential for self comprehension.

B. THE EEG PROJECT

The areas being pursued by the team at this time include computer modeling of neural systems, acquisition and analysis of raw EEG data, programming and digital signal processing, construction and testing of tasking mechanisms and peripheral equipment, and finally, data analysis and publication of results. There are normally four or five active project members under the guidance of Professor George Marmont.

C. THE AUTHOR'S CONTRIBUTION

The author has been involved with this project for about two years. During this period, the author has contributed to the design and construction of the tasking mechanism and the integration of this critical subsystem into the experimental setup. Many hours were spent as a subject assisting the team and individual thesis students. The author's main contribution is this evaluation of the team's progress toward experimental verification of the "preferred" frequency hypothesis.

II. BACKGROUND

A. THE ELECTROENCEPHALOGRAM AND MODERN SIGNAL PROCESSING

The English physician Robert Caton first reported electrical potential differences recorded from the brains of rabbits and monkeys in 1875. Caton noted the high ambient noise level of such recordings even though his instruments were of the crudest sort [Ref. 15].

The limitations of EEG research have been and continue to be based on equipment and data processing techniques. There are basically two considerations with this type of signal processing:

1. Low Signal Level

The qualitative restrictions on equipment necessitated by measurement of potential differences of tenths of microvolts (10^{-7}) are significant. Continual monitoring of system performance and state of the art improvement are necessary.

2. Noise Level and Multipath Considerations

The EEG is the algebraic sum of signals from many sources in the brain. Multisource propagation and high ambient noise level are serious signal processing problems. The separation of the signal of interest from the source of interest requires novel programming techniques and current digital computer technology.

B. THE HYPOTHESIS

It is the hypothesis of this thesis that there exists a "preferred" frequency bandwidth in the EEG for the activity carried out during the experiment. The experimental method links bandwidth and performance criteria. Details are described in later sections.

C. TEGULOMETRIC FREQUENCY ANALYSIS

Tegulometric Frequency Analysis is one of the important methods of signal processing work at the Naval Postgraduate School Bioengineering Laboratory. The Naval Electronics Systems Command feels that the method has sufficient merit to justify funding. Professor George Marmont is the author of the supportive programming for the tegulometric method.

D. PREFERRED FREQUENCY

For the purposes of this report, a "preferred" frequency means a dominant freuqency bandwidth or frequency component connected with a specific activity. The dominance of these frequencies is derived from the proportion of time they are present, not their power.

E. FEEDBACK

Feedback is a term that is applied in many areas. The word "feedback" can have electrical, control, administrative and psychic connotations depending on the listener.

The use of the term "feedback" will be restricted to the following definition for the purposes of this report.

Feedback is a stimulus, based on real time data, which is returned to the subject in real time and utilized by the subject to ascertain an evaluation of his performance. It is noted that the evaluation by the subject of this feedback is highly variable. The feedback stimulus for this experiment is diffuse white light projected onto a screen placed behind the tasking device.

The visual stimulus is included as feedback in order to possibly enhance the preferred frequency associated with the experimental task.

F. POSSIBLE APPLICATIONS

Improvement of performance through the use of feedback stimuli keyed to task related preferred frequencies has many applications. Most operational watch standing and flying billets within the Navy consist of simple, repetitious tasks where system performance and operator attention level are intimately connected. With system costs for a destroyer type ship approaching one billion dollars, and single aircraft costs at twenty million dollars or more, any improvement in system performance through operator performance enhancement techniques is highly cost effective.

Applications also might include: screening of applicants before costly training resources are wasted, shortening of training cycles, optimization of console design and more efficient utilization of personnel resources. The benefits would be numerous and the impact on improved system performance with no additional capital investment would be substantial.

III. PHYSIOLOGICAL CONSIDERATIONS

A. GENERAL

The concept of preferred frequencies as the basis for information processing in the brain necessitates a supporting physiological argument. It may be stated that the primary functions of the brain are the transfer and processing of information from one point to another within the nervous system. Sensory inputs are first translated into nerve impulses, the language of the nervous system. All information processed in the brain is processed via these coded transmissions. Abstractions such as learning and memory are not exceptions [Ref. 5].

The basic unit of the brain and the remainder of the nervous system is the neuron. There are enormous numbers of these cells within the nervous system; representative estimates for the cerebral cortex alone approach five billion individual units. Studies have indicated that the interconnections for a single neuron with others may be on the order of several hundred to several thousand [Ref. 18].

The magnitude of the above numbers emphasizes how intricate these interactions between various areas of the nervous system are. Also, it serves to illustrate that any attempt to characterize brain activity in exact spatial and temporal terms has no chance of success utilizing procedures available today. Hence the statistical correlation methods adopted by the laboratory team.

B. THE NEURON AND SYNAPSES

As has already been stated, the neuron is the fundamental structural unit of the nervous system [Fig. 3-1a]. It is advantageous to explore the characteristics of the neuron which enable it to be exploited by synchronous detection methods.

The individual neurons communicate by means of fine branches of their respective axons that make contact with other neurons' surfaces and end in little knobs scattered over their somas and dendrites. These contact areas are specialized sites of communication called synapses. All information is transferred at these sites and the correct functioning of the electrochemical transmission across the synaptic cleft is absolutely essential. Data about the body and its environment is passed via the mechanism of synaptic transmission [Fig. 3-1b].

C. PHYSIOLOGICAL ORIGIN OF FREQUENCY CODED INFORMATION

A neuron is excited or inhibited through synaptic activity on its soma or dendrites. Excitation or inhibition depends entirely on the nature of the transmitting substance that is released into individual synaptic clefts. In other words, it is possible for an individual neuron to receive both excitatory and inhibitory pulses; however, the firing of the neuron depends only on excitation to threshold. This single pulse, which is the result of possibly hundreds of summated inputs, then travels as a discrete entity down the

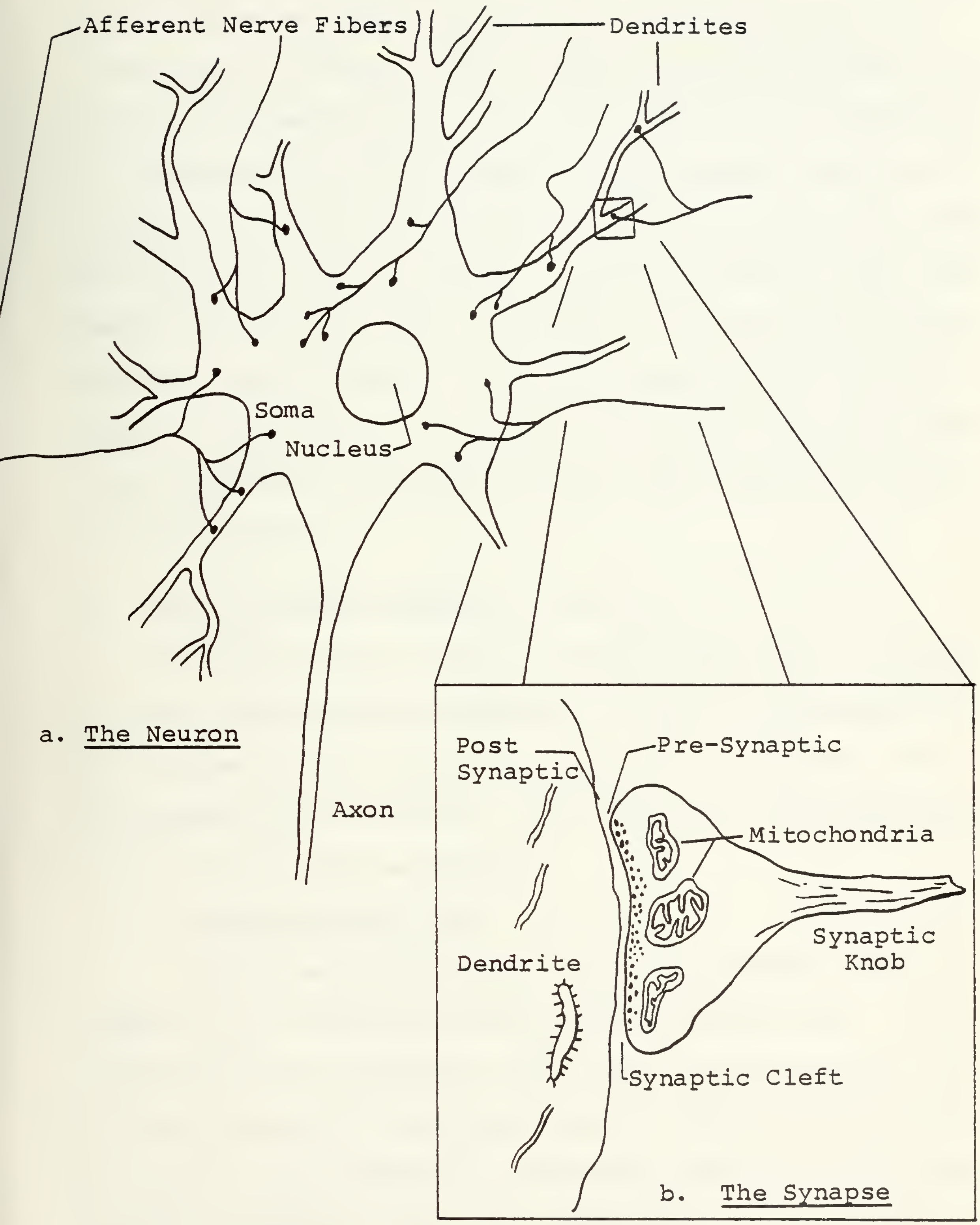


Figure 3-1. Neuron with enlarged view of Synapse.

axon and its branches to synapses with other neurons. It should be stated that a neuron has to be excitatory or inhibitory; it cannot serve in both roles even though it is capable of receiving both types of transmitting substances.

The result is the propagation of uncounted millions of uniform pulses which transfer information about time, space and intensity through complex frequency coding. This vast amount of data is somehow organized and woven into logical patterns that we sense as physical experience or abstract thought. The idea of a specific frequency code associated with a particular activity is one of the principal themes of this research.

D. BASIS OF BRAIN ELECTRICAL ACTIVITY

The origin of the changes in potential which are sensed by the scalp mounted electrodes is based on the nature of the tissues through which the potential differences are propagated and the cellular units and their interconnections which act as localized sources.

1. The Pyramidal Cell

The somatomotor area [Fig. 3-5] contains large numbers of so called pyramidal or giant Betz cells. It is suspected by the laboratory team that pyramidal cells are strongly related to the EEG; that is, they are responsible for most of the measurable electrical activity. In a sense, a single pyramidal cell can be considered in input/output device. There also exist large numbers of smaller stellate

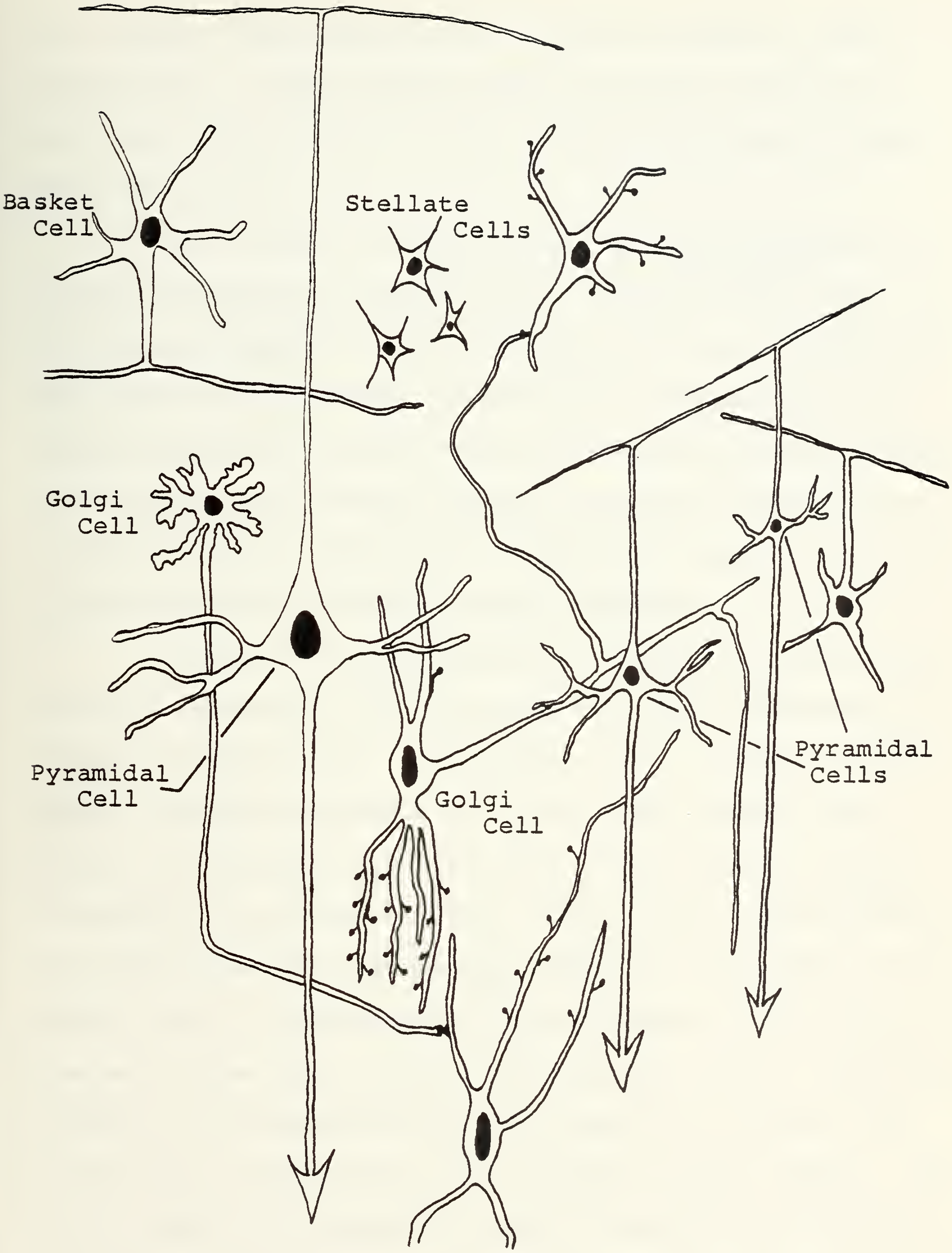


Figure 3-2. Idealized Cortical structure showing horizontal and vertical constituents.

and granule cells which serve to make horizontal interconnections. These smaller cells are among others that have been identified, but they are not of primary concern here [Fig. 3-2].

The cortex is characterized by the occurrence of a large percentage of pyramidal and stellate cells [Ref. 8]. The larger pyramidal cells are known to extend through most and sometimes all levels of the cortex. Pyramidal cells extend vertically through the cortex making numerous interconnections with afferent fibers, pyramidal elements and others. They are the most susceptible to electrical stimulation of all the cortical neural elements.

Figure 3-3 demonstrates how a potential difference could be developed in the interstitial fluid surrounding a single pyramidal cell. It supposes that a single incoming action potential synapses with the apical dendrite and results in a slight depolarization of the neural membrane adjacent to the synaptic cleft. This slight depolarization will propagate down the apical dendrite to the soma of the neuron until an electrically uniform state of equilibrium is reached between the internal and external fluid. Momentarily, however, this depolarization will result in current flow through the interstitial fluid as shown in the figure. Now, if the effect of integrating tens of thousands of similar, synchronously occuring events is measured, the result is detectable electrical activity on the scalp.

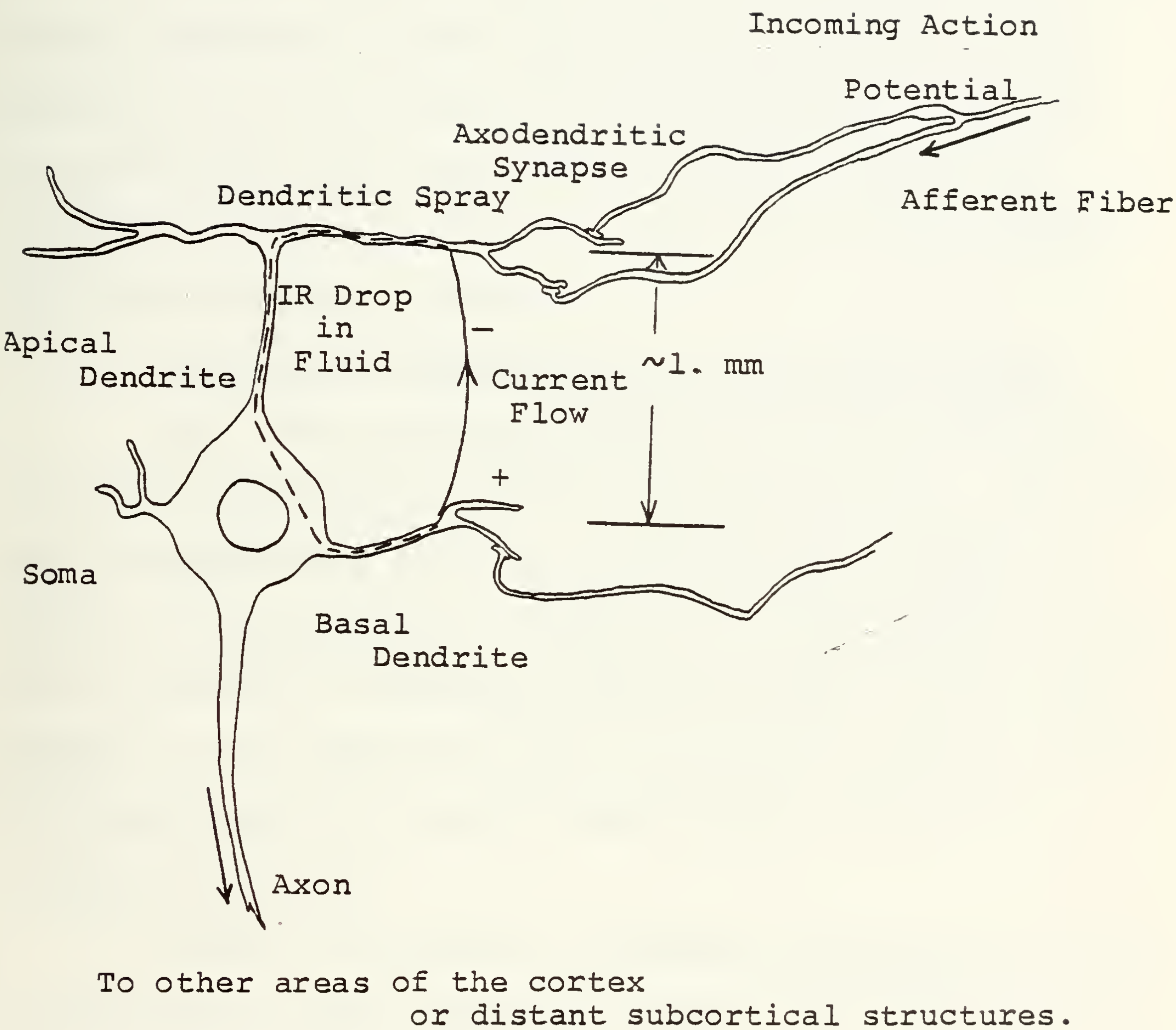


Figure 3-3. IR drop with pyramidal cell.

If the occurrence of the well documented alpha wave is considered, it becomes apparent that many cells must contribute to the resultant electrical activity. The alpha frequency is around ten hertz and a single action potential is on the order of one millisecond. The only imaginable way that these lower frequency waves could originate would be synchronous activity of large numbers of neurons acting in concert.

2. Propagation Considerations of the Head Tissues

The scalp potentials measured are the consequence of synchronous neural activity within the brain. The brain and its encasing tissues may be considered a volume conductor of this activity. Attempts have been made to model this volume as a uniformly conducting sphere with a single dipole in the cortex [Ref. 12]. It is the author's contention that this is a vastly oversimplified approach to a complex structure.

Figure 3-4 presents a somewhat diagrammatic section of the skull in the transverse plane. The conductivity of the tissues shown vary from 0.0002 mhos per centimeter for the skull to 0.0033 mhos per centimeter for the cortex [Ref. 12]. Cortex and bone are not the only tissues present. Blood, cerebro-spinal fluid, various nuclei of different conductivity and other discontinuities are present and contribute difficulty by introducing phase delays. These delays tend to mask actual frequencies and increase the

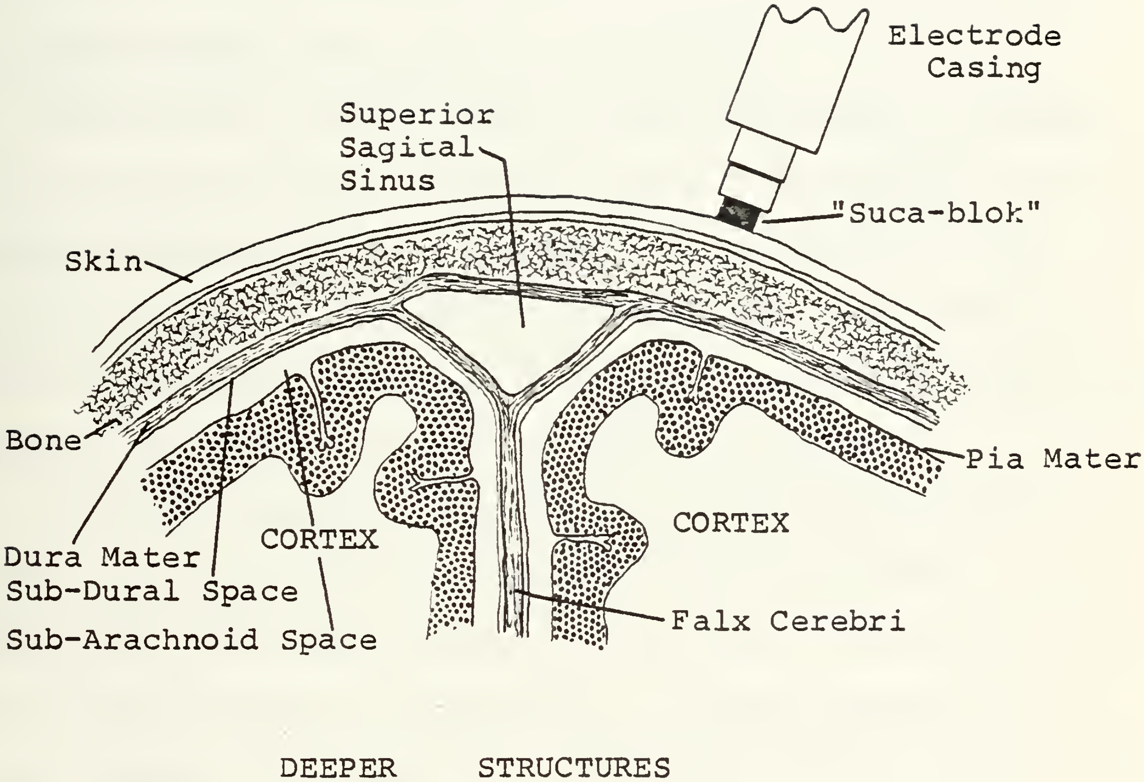


Figure 3-4. Cross Section of the head [Ref.10].

complexity of a problem already complicated by background noise.

It would be more accurate to characterize the brain and its surrounding tissues as a multisource, multipath conductor. Hence the statistical detection techniques utilized by the laboratory team.

E. PHYSIOLOGICAL DESCRIPTION OF THE TASK

The selection of the task utilized was based on several years of effort by the laboratory team. The details of the tasking mechanism will be covered in a later section of this paper, but it should be stated at this point that the team was primarily concerned with consistency, reproducibility, simplicity and the retention of subject interest.

The task simulates an operator control problem not unlike those related to aircraft piloting and radar or sonar operations. The task consists of centering a dot on an oscilloscope which is disturbed in a random fashion by a pseudo-random pulse generator constructed by the author. The subject is provided with real time visual feedback as a data run progresses.

The subject sits in the darkened screen room in as relaxed a state as possible. A recliner with the force stick control attached is used in order to minimize the movements of the subject while still allowing him to perform the task. Everything possible is done to ensure that what

is measured by the electrodes is related to brain activity in response to the task.

Experimental interest is confined primarily to measuring responses at the cortical level connected with the task. Reflex arcs, activity in deeper brain centers and the physiology of motor control are not ignored. Reference 4 provides much useful information on these topics.

Figure 3-5 is a lateral view of the left side of the brain. It presents the dominant hemisphere for right handed subjects. Of particular interest are the so-called motor and premotor areas and the frontal eye field. The approximate location of various motor areas are functionally labeled [Ref. 18]. The task and placement of electrodes are designed to elicit and then measure activity in the shaded areas associated with the frequency band of interest.

The darkly shaded area contains the giant pyramidal cells of Betz and is the most sensitive to electrical stimulation of any area on the cortex. Low levels of excitation will result in discrete motor movement, sometimes twitches of single muscles. Large myelinated fibers originate with these giant Betz cells and travel through the corticospinal tract to the anterior motoneurons of the spinal cord. Also, axons of the giant Betz cells send collaterals to subcortical processing areas which in turn may feedback to the motor area [Ref. 8]. The existence of intracortical feedback circuits contributes to a proposed model of a reverberating

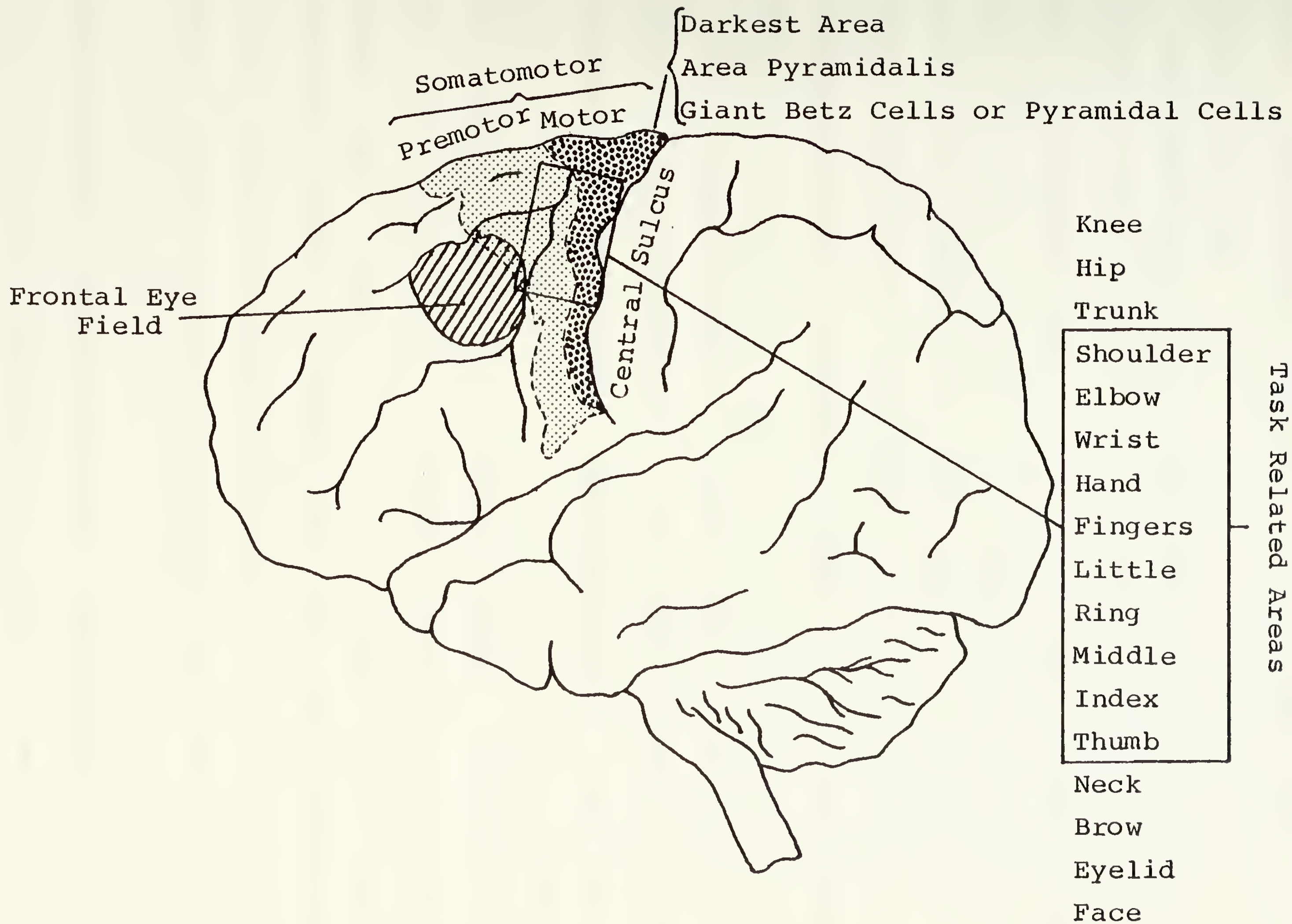


Figure 3-5. Lateral view of the left side of the brain [Refs. 8, 18].

neural circuit presented in the next section of this paper. Experimental efforts are concentrated in this area because of the likelihood of observing a significant level of task related activity.

Representation in the somatomotor cortex is directly related to the discreteness of movement required of the body part in question. Areas such as the hand, fingers, thumb and mouth have relatively large representation as compared to, say, the trunk of the body [Ref. 8]. This relatively large, excitable area dedicated to the right arm and its constituent parts is highly suitable for this experiment. Hence, data collection effort naturally concentrated here.

The lighter shaded or premotor area, which is one to three centimeters anterior to the area pyramidalis, demonstrates somewhat different characteristics. Much more electrical stimulation is necessary for a motor response and the stimulus has to be of longer duration. Movement connected with this anterior area is slower to develop and involves larger muscle groups. This is in contrast to the discrete twitches elicited by stimulation of the area pyramidalis. Signals from this premotor area are sent to the area pyramidalis and the extra-corticospinal tracts [Ref. 8].

The cross hatched area of Figure 3-5 approximately delineates the frontal eye field. Stimulation of this area elicits binocular movements of the eyes, movements of the head and pupillary dialation. Voluntary and reflex eye movements are mediated by the frontal eye field and its projections [Ref. 18].

F. MYOGRAMS

The broad band electrical phenomena observed when muscles are contracted are called myograms. Careful consideration is given by the research team to their elimination.

Figure 3-6 is an idealized sketch of the left side of the head. Major muscle groups that could impact on EEG data are noted. The epicranius muscle is a broad sheet of thin tissue which is anchored above the eyebrows and at the base of the skull. The temporoparietales and masseter muscles act in concert when the jaw is tightened [Ref. 11].

Figure 3-7 is a graphic demonstration of myograms as they appear after processing. They are characterized by easily discernible large amplitude, pulse like waves. Data runs where myograms appear are disgarded.

The laboratory team is acutely aware of the havoc myogram type effects can play with data. Every effort is made to ensure the effects are minimized.

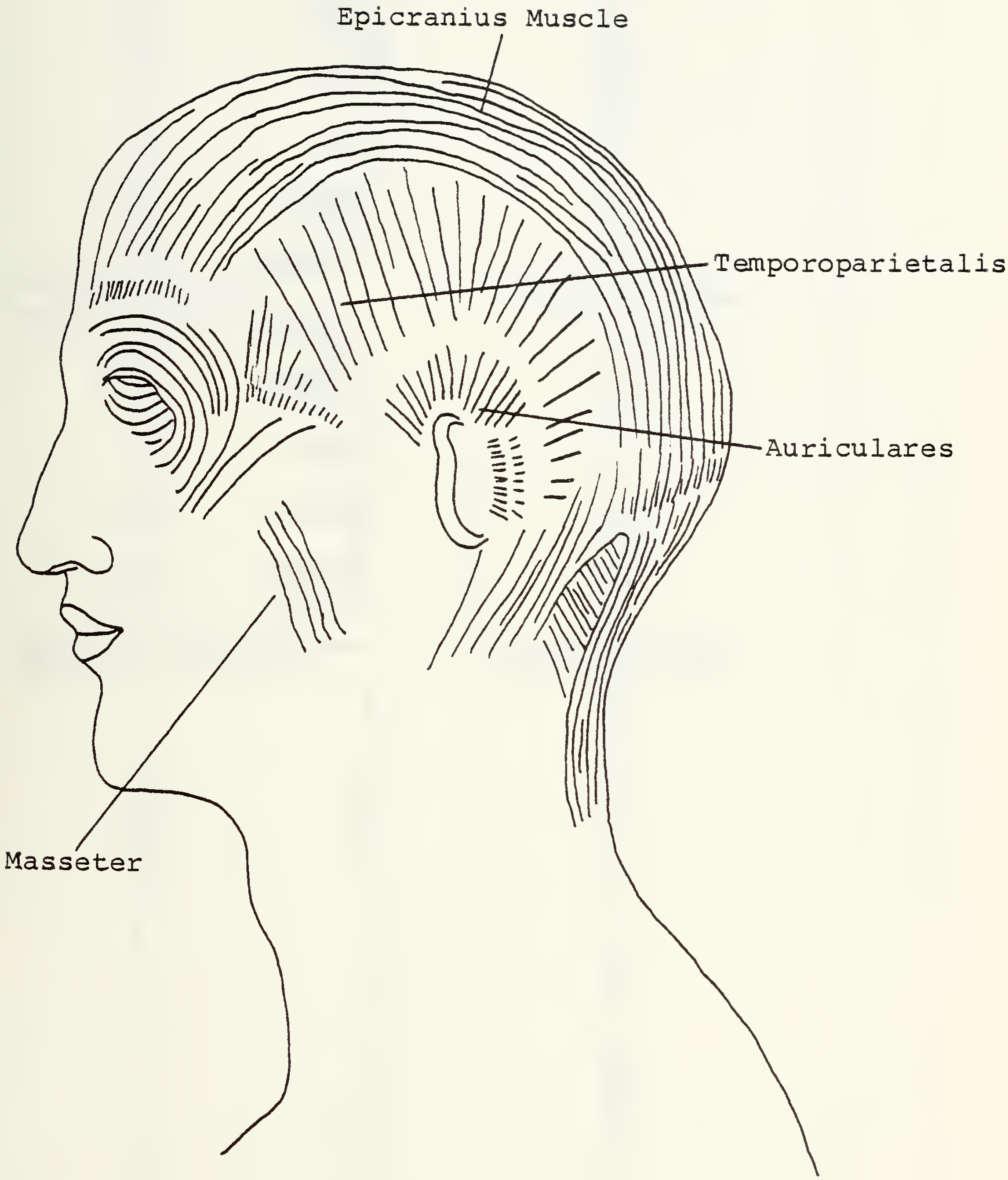


Figure 3-6. View of the left side of the head detailing major muscle groups.

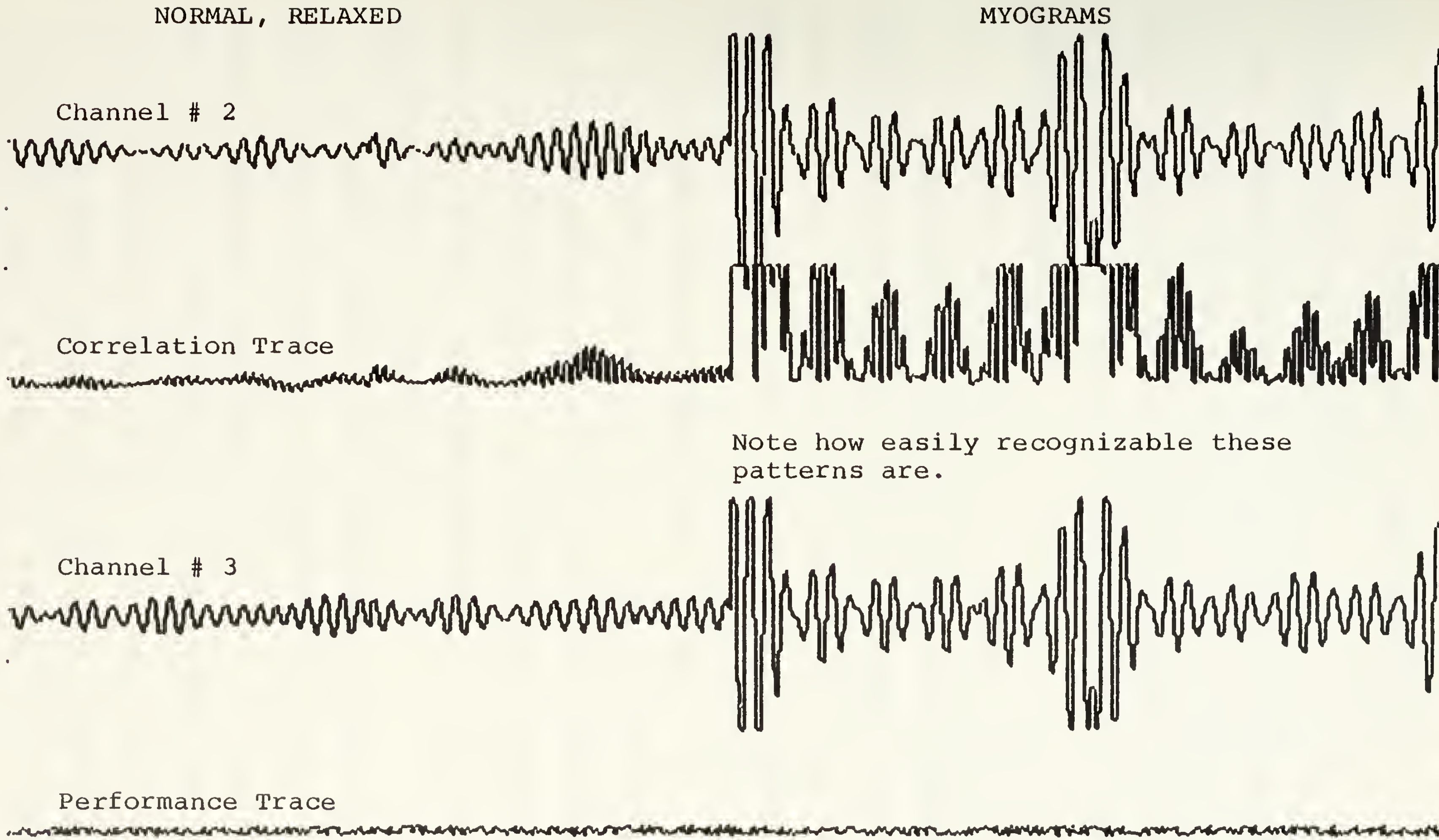


Figure 3-7. Processed data sample showing characteristics of myograms.

IV. NEURAL CIRCUIT MODELING PROJECT

A. NEURAL CIRCUIT SIMULATION

The laboratory team has attempted to simulate several basic neural circuit arrangements utilizing the PDP 11/40 digital computer. There were several reasons for this work:

1. Training in the use of the computer and machine language programming.

2. Greater appreciation of how neural circuits work.

3. Demonstration through simulation that frequency of output in a neural circuit can be controlled. It is worthwhile to include some of these results here because it aids in understanding the term preferred frequency.

B. A SIMPLE NEURAL REVERBERATING CIRCUIT

Figure 4-1 is an example of a simple neural circuit. It utilizes relatively few excitatory and inhibitory pathways; yet the capability of increasing the receptivity of the output neuron B to pulse patterns of a particular frequency band is demonstrated.

Excitatory inputs do not necessarily result in the neuron being stimulated to threshold and firing. Post synaptic potential sometimes varies as a scalloped shaped wave [Fig. 4-2] without firing if excitatory and inhibitory inputs are sequentially correct. Firing is an all or nothing event that depends only on excitation to threshold. Neuron firing is followed by a refactory period during which it is not possible to fire.

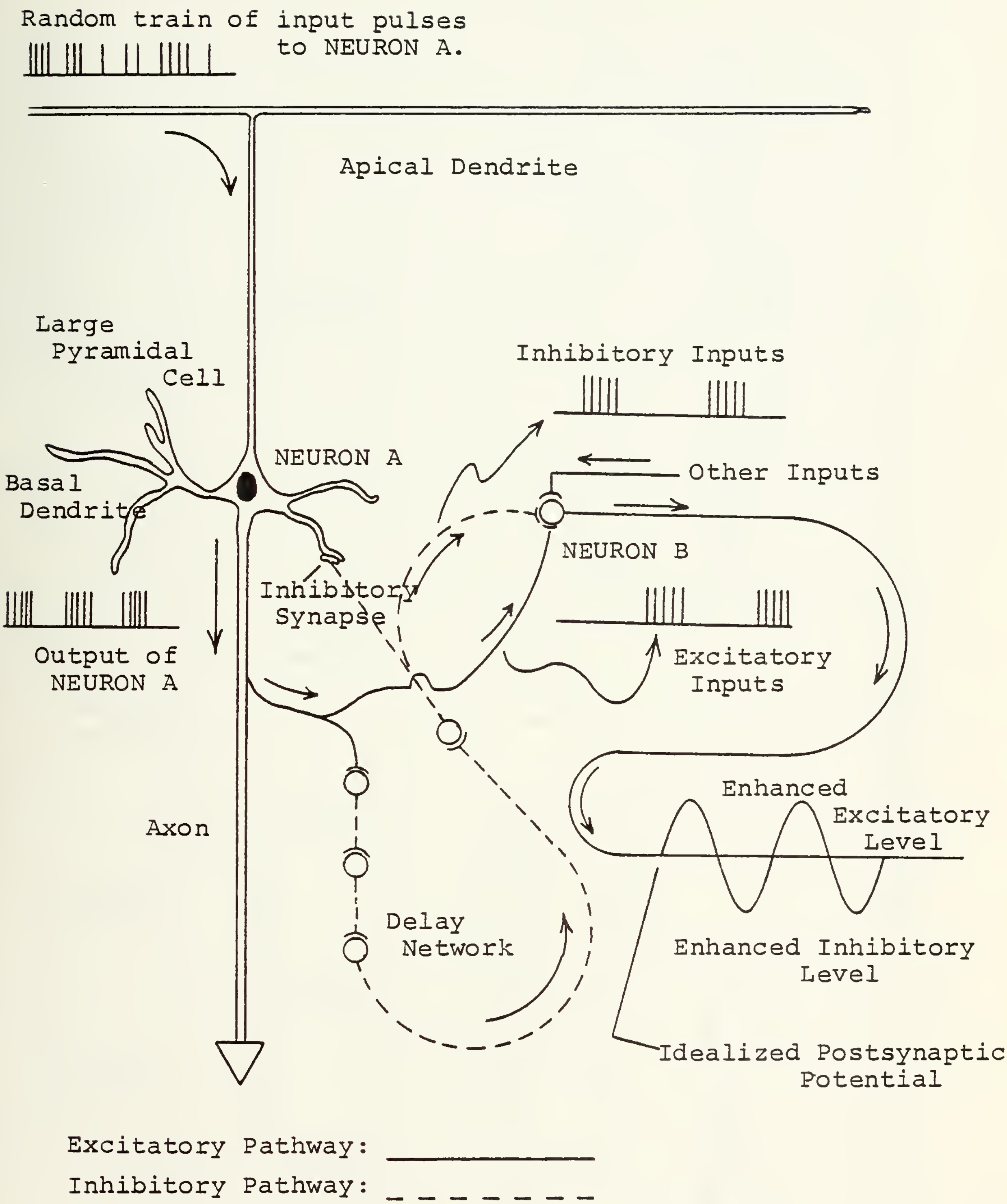


Figure 4-1. A simple neural reverberating circuit.

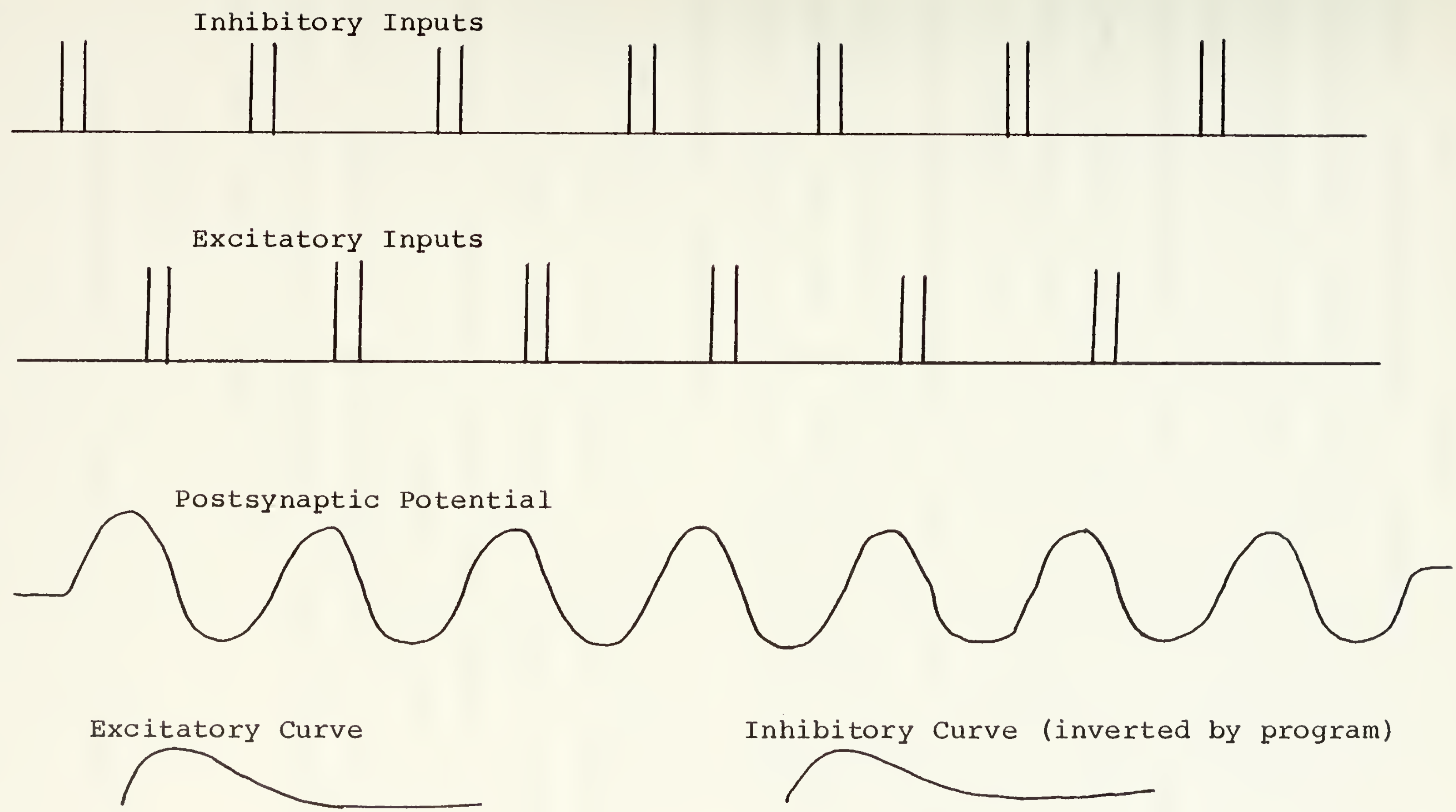


Figure 4-2. Scalloped waveform characteristic of the Postsynaptic Potential.

A random train of excitatory pulses travels down the apical dendrite of neuron A, a pyramidal cell. Neuron A integrates this series of pulses. The output of neuron A would normally be a somewhat uniformly spaced pulse train; instead, there is an inhibitory synapse feeding back on the basal dendrite which causes the output to be uniformly spaced groups of pulses. These groups of excitatory pulses branch from the axon of neuron A and proceed as illustrated to a branching point; one side an inhibitory delay network and the other an excitatory branch direct to synaptic contact with neuron B, which may be a pyramidal cell. Meanwhile, the train of inhibitory pulses has made its way through the delay network to branch to the basal dendrite and neuron B respectively.

The effect on neuron B of these two synapses is shown in Fig. 4-1 as the oscillatory line which represents the resulting post-synaptic potential. Neuron B has been made receptive to excitatory pulses which arrive at the peaks of the wavy line labeled as "enhanced excitatory level". This simple network has a marked propensity to fire at a certain enhanced or preferred frequency. Note that provision is made for other inputs at neuron B.

C. A SIMULATION

The configuration of Figure 4-1 is simulated in the following plots from programs written during the neural modeling project. Each example consists of two pages; the

first is a record of the simulation including excitatory inputs, inhibitory inputs, post-synaptic potential, and an output trace, the second is a DFT of the resulting post-synaptic potential trace.

The DFT plots are particularly interesting because they make readily apparent the phenomenon of enhancement to a certain preferred frequency. The examples were somewhat deliberately picked to emphasize 80 Hz.

Please see the plots for additional explanation.

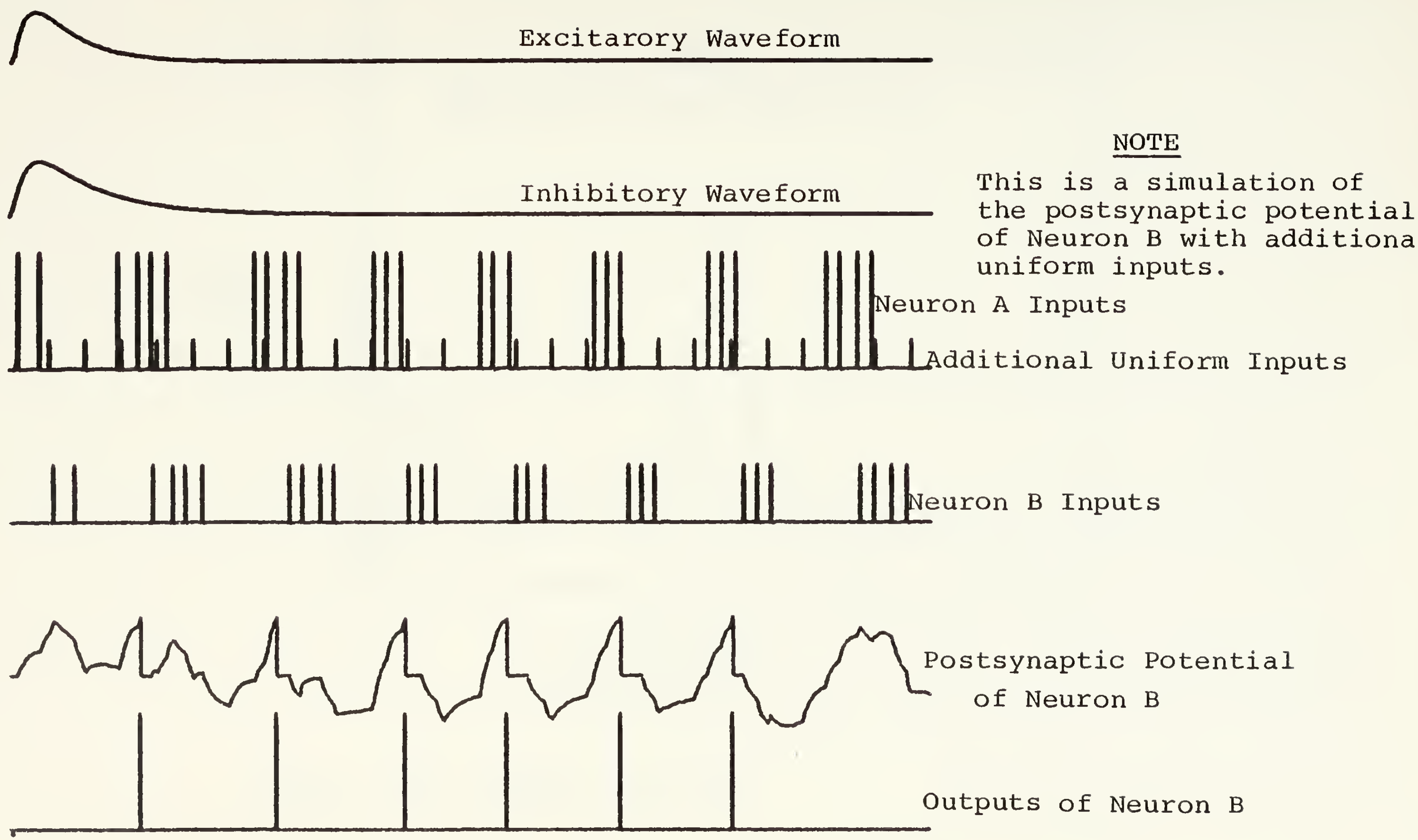


Figure 4-3a. Example EIPSP Plot.

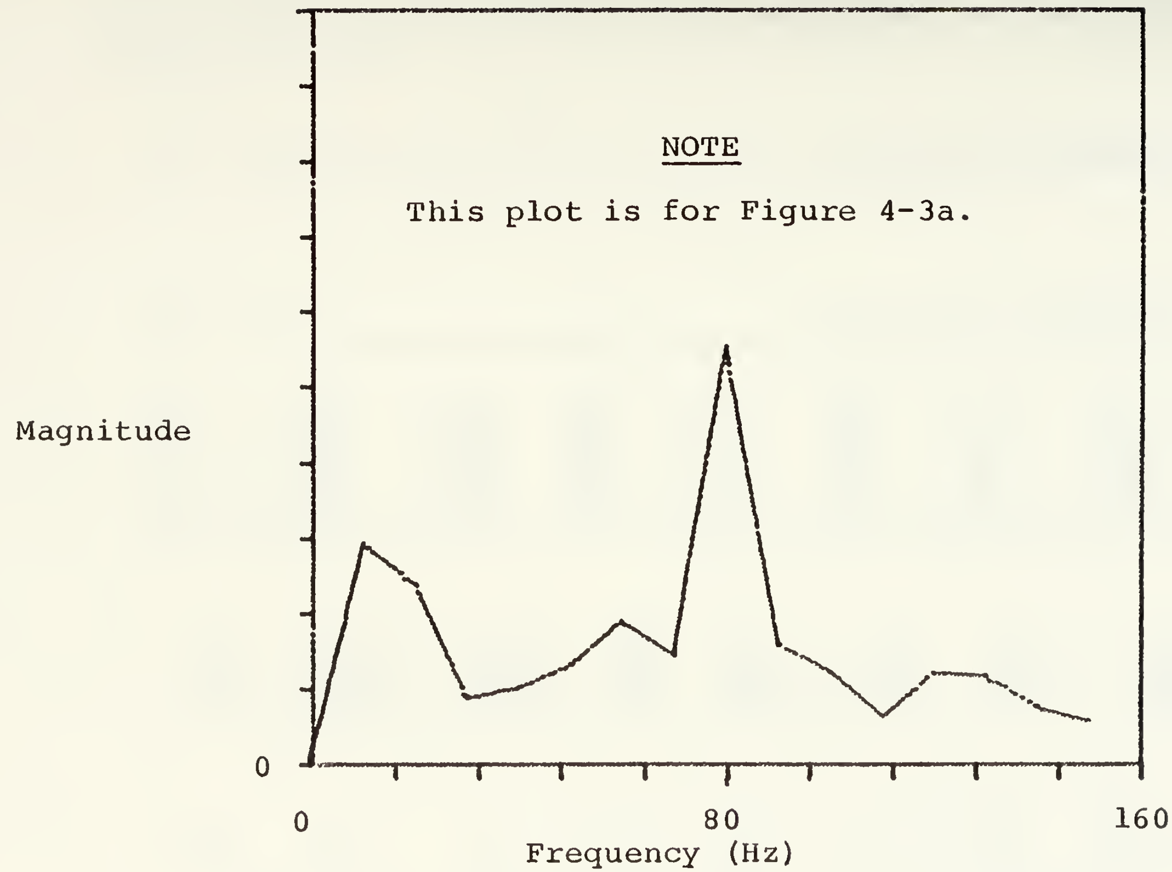


Figure 4-3b. Example DFT Plot.

NOTE*

This figure demonstrates the increased probability of firing at the peak of the enhanced excitatory part of the postsynaptic potential trace.

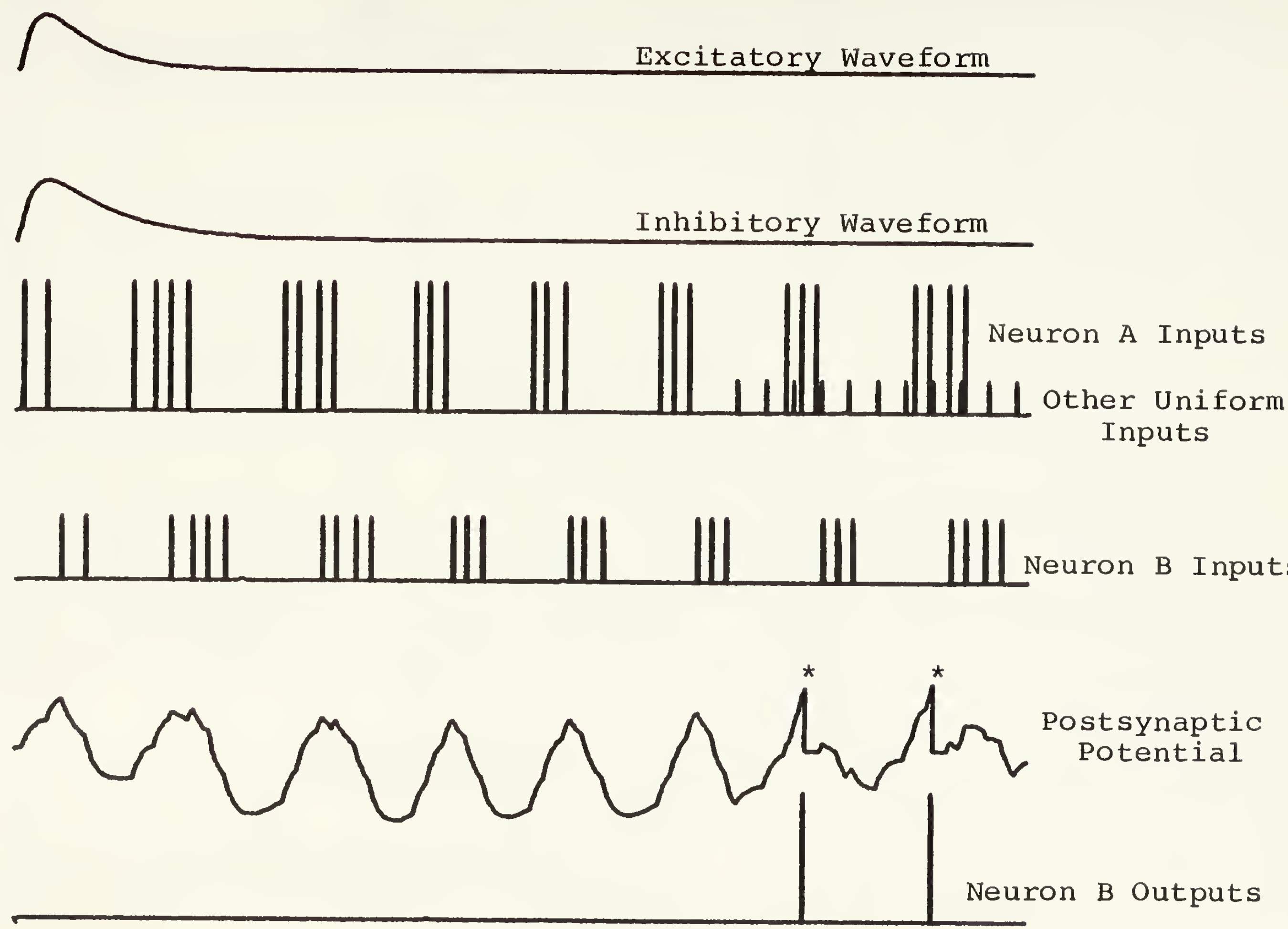


Figure 4-4a. Example EIPSP Plot.

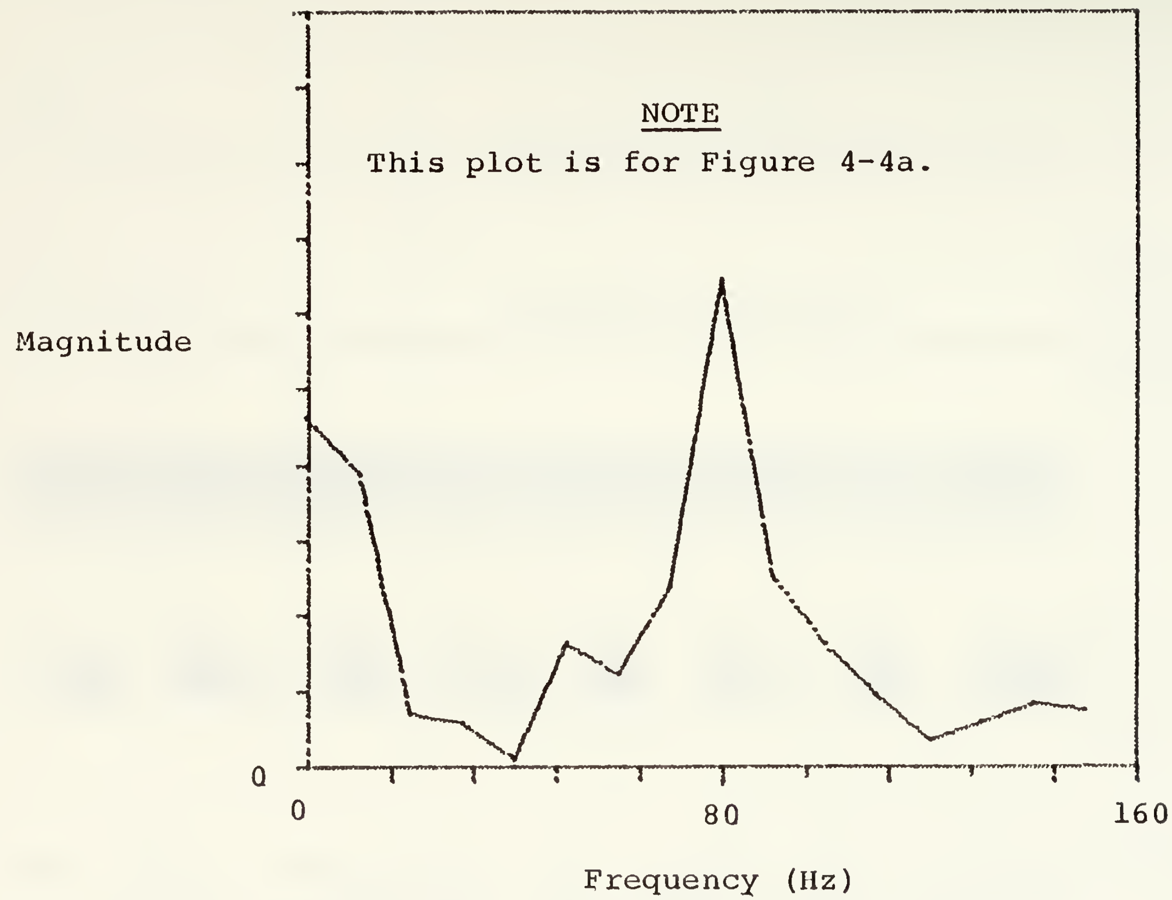


Figure 4-4b. Example DFT Plot.

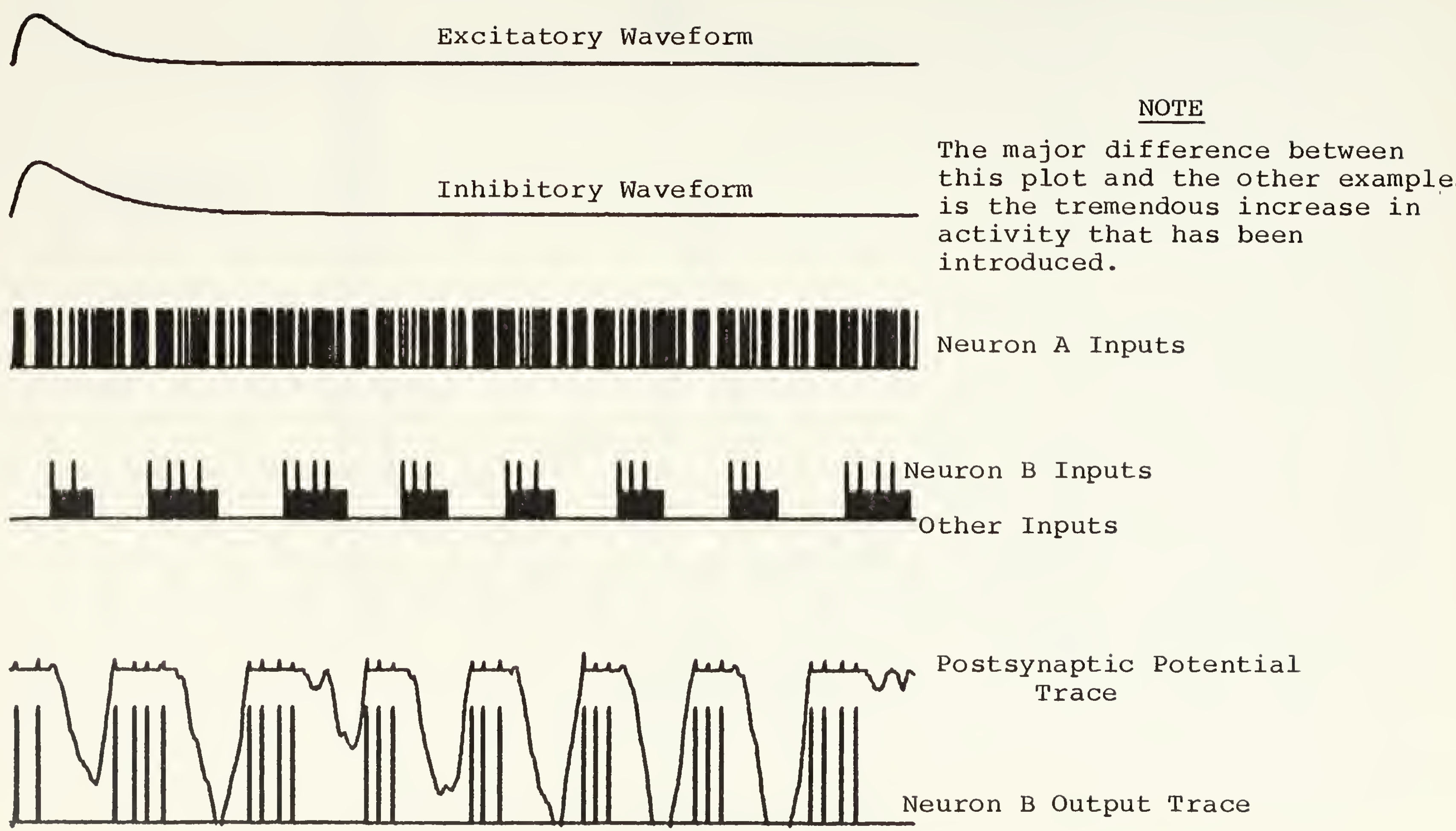


Figure 4-5a. Example EIPSP Plot.

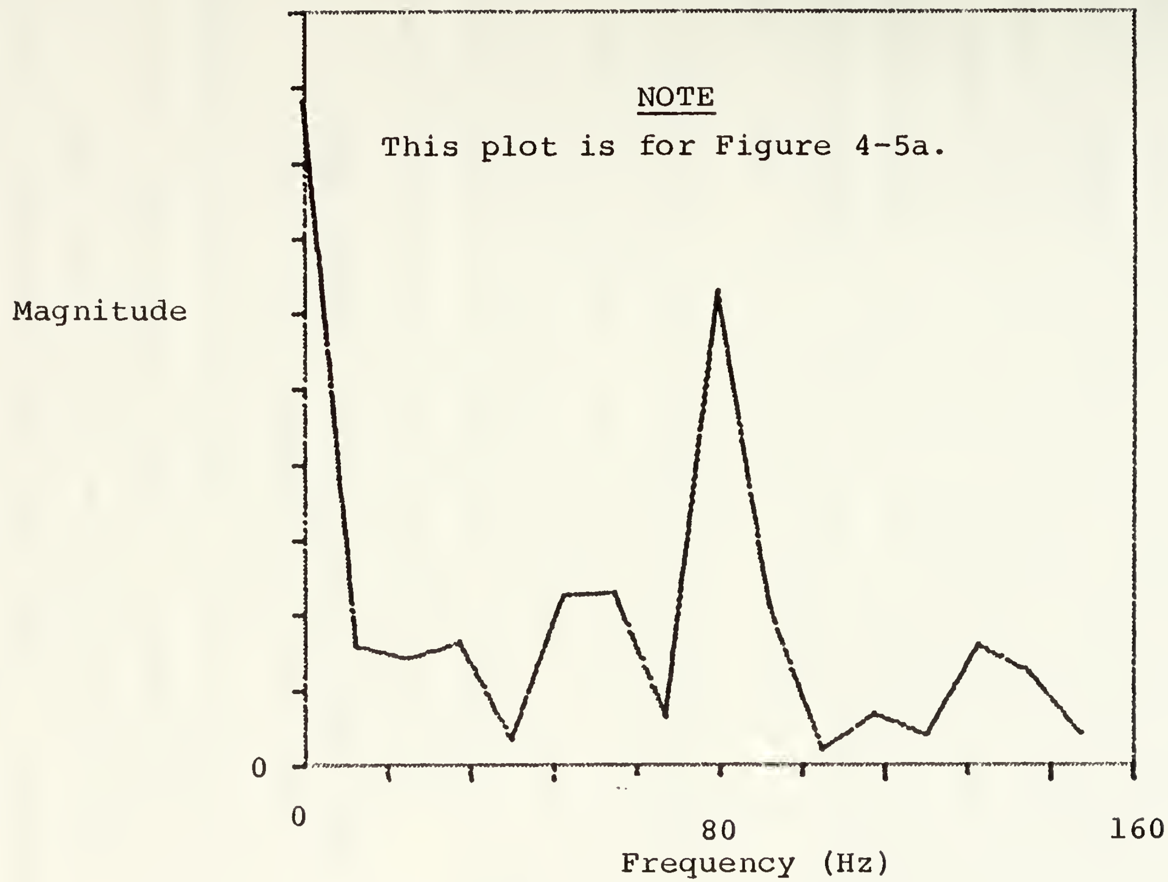


Figure 4-5b. Example DFT Plot.

V. EQUIPMENT DESCRIPTION

The experimental equipment configuration is the result of several years of work by the laboratory team. The requirements which are met in order for the experimental effort to be successful are based primarily on the large amount of data which are processed and stored in real time. Digital Equipment Corporation's PDP 11/40 digital computer has proved to be very satisfactory as a central processor.

Figure 5.1 is a block diagram which shows the interconnections for the entire data collection system. In the system description which follows, each major component and its functions will be briefly discussed.

A. ANALOG DATA CONDITIONING PERIPHERALS/DIGITAL COMPUTER

The PDP 11/40 and its associated peripherals are, as has already been mentioned, the heart of the data manipulation portion of the experiment. Reference 3 contains detailed skematics of the following devices:

1. Eight Channel Differential Preamplifier

Initial data conditioning occurs here. This preamplifier is one of the more critical peripherals because it is here that the EEG signals are amplified to a usable level. This amplification must be accomplished with minimal distortion and non-linear phase delay. The ever-present 60 Hz interference also has to be contended with at this

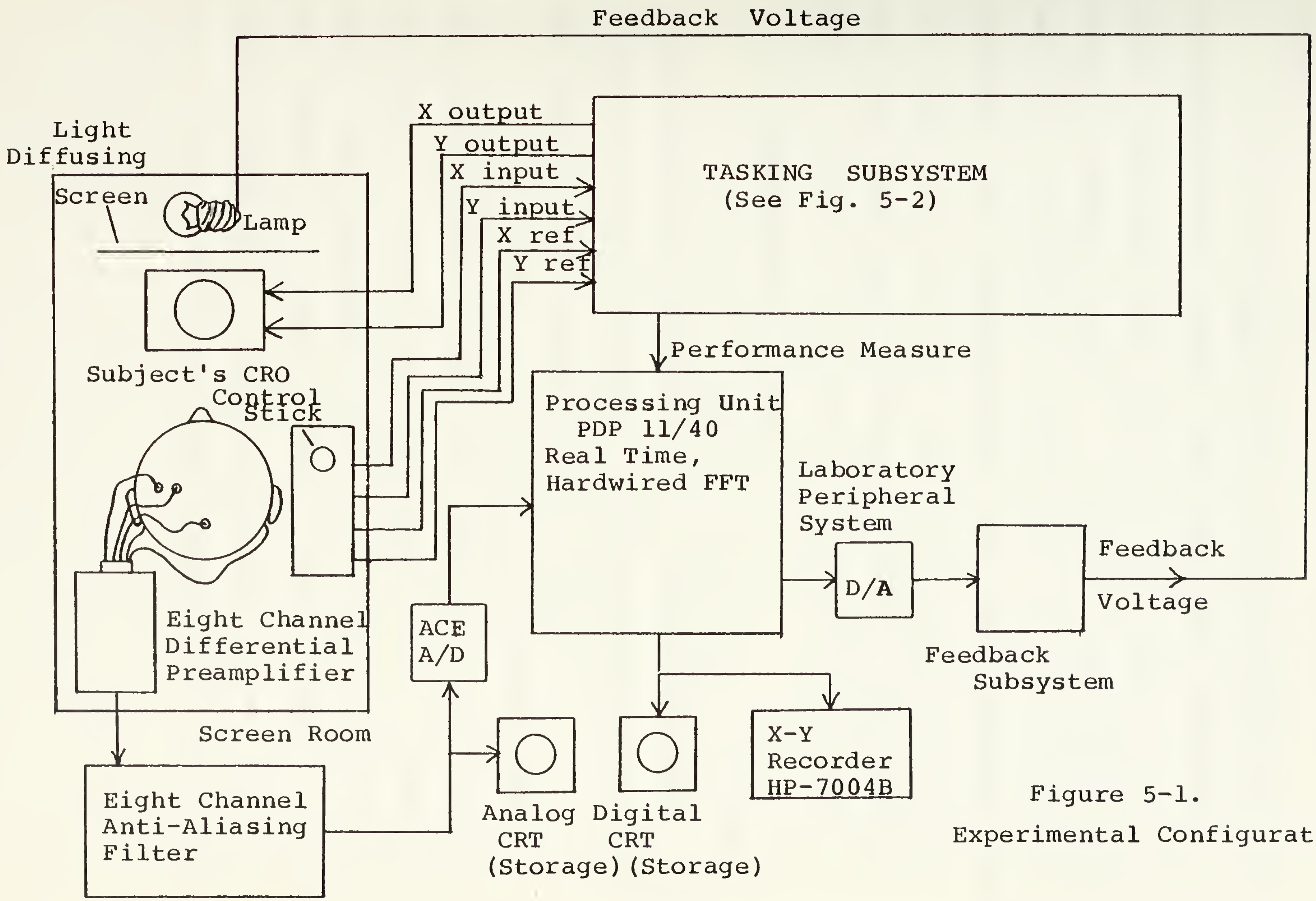


Figure 5-1.
Experimental Configuration

stage of amplification or it becomes an overwhelming problem.

The differential preamplifier is constructed with two amplification stages. Each stage has a differential input. The common mode rejection ratio (CMRR) of the two stages is ideally 24,000:1. The actual operational CMRR is somewhere around 6000:1; variability occurring because of electrode noise considerations, etc. The operational amplifiers used are Burr Brown 3521K and they were selected after much searching to ensure optimal low noise performance. The overall gain of the preamplifier is 3850.

2. Anti-Aliasing Filters

In all digital sampling schemes there is danger of higher frequencies masquerading as lower frequencies. This aliasing is caused by higher frequencies folding into the band which is being tested at the sample rate.

The filters in use are four pole Butterworths. The filter response is set to be down 3 db at 256 Hz and 24 db at 512 Hz for use with the program TWODET. Another advantage of the Butterworth filter is its linear phase response. The filter is an active device utilizing Fairchild μA740 operational amplifiers. The gain from both filter stages is 2.57. This implies the overall preamplifier/filter gain is around 10,000.

3. <u>Analog Conditioning Element</u>

This is the device that actually makes the analog to digital conversion of the preamplified and filtered data. The sampling rate is a parameter that is varied depending on the bandwidth of the data desired. For example, a sampling rate of 4096 samples per second, fulfilling the Nyquist criterion for 2048 Hz, is typically used for wideband EEG exploration.

All channels are sampled at the same time to prevent any sort of artificial phase delay between channels. This device also acts as a multiplexer with direct memory access (DMA).

B. TASKING SUBSYSTEM

The purpose of the tasking subsystem is to provide a reproducible, variable task to the subject and a useful indicator of performance for data manipulation. Figure 5-2 diagrammatically represents the tasking subsystem. The subsystem consists of five modules plus a light emitting diode (LED) display of the subsystem state. Reference 1 provides detailed information on this equipment.

1. <u>Pseudo-Random Pulse Module</u>

This module is of the author's design and construction. It contains the clock, shift registers, exclusive-OR, monostable multivibrators (one shot), and LED drivers. The outputs are sent to the LED display, and to the performance indicator module for mixing as a trigger indicator, and to

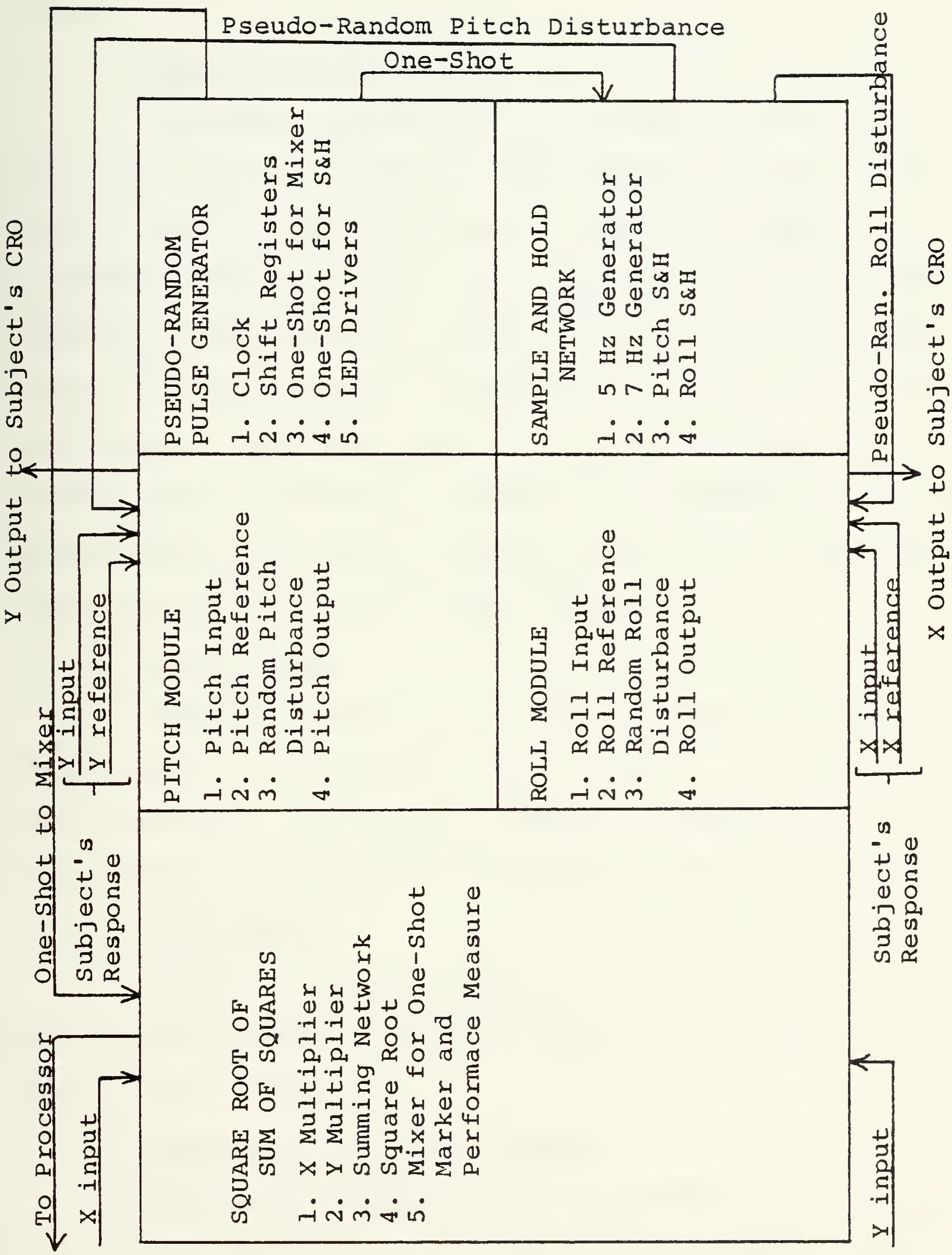


Figure 5-2. Tasking Subsystem.

the sample and hold module as the sample and hold trigger pulse.

2. Sample and Hold Module

This module contains the 5 Hz and 7 Hz sine wave oscillators for the pitch and roll sampled voltages. The pseudo-random trigger pulse causes these two waveforms to be sampled simultaneously. The sample of the 5 Hz waveform determines the amplitude of the X axis or roll disturbance and the 7 Hz determines the amplitude of the Y axis or pitch disturbance. Since the 5 Hz and 7 Hz oscillations are obviously not harmonically related, the disturbance generated appears random in timing, amplitude, and phase. They are then sent to the pitch and roll modules.

3. Pitch Module

The pitch module controls the deflections on the vertical axis of the subject's CRO display. It is here that the control stick input (subject's reaction) and the pseudo-random sampled pitch deflection voltage are mixed.

4. Roll Module

The roll module provides the same functions as the pitch module except it controls horizontal movement on the subject's CRO display.

5. Performance Indicator Module

This module determines the magnitude of the displacement of the CRO dot from the center of the screen. It accomplishes this task through a network which includes two

multipliers, a summer and a device which computes the square root of the sum of the squares. This output is then mixed with the one-shot from the pseudo-random module and sent to the computer as a marker of disturbance time.

C. HELMET AND ELECTRODES

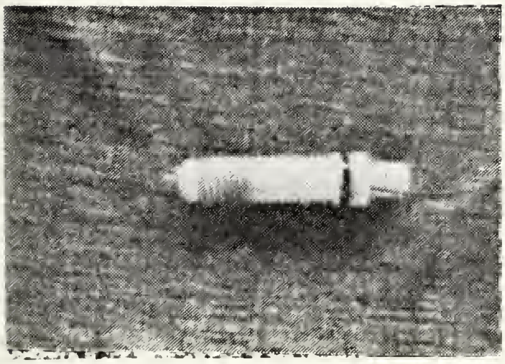
The present configuration of helmet and electrodes is the result of several iterations constructed by the laboratory team. The lightweight, comfortable arrangement is pictured in two views in Figure 5-3.

The helmet is a modified rock climbers hard hat which has had numbered holes cut in it. Rotatable circular sections are mounted in these openings to allow fixed access to all parts of the scalp. Each circular section has four threaded holes for placement of electrodes.

The Beckman skin electrodes are mounted in specially machined plastic cylinders which are inserted and locked into another threaded cylinder for insertion into the circular sections. Figure 5-4 shows photographs of an electrode in both the assembled and disassembled configurations. See also Figure 3-4.

Contact between the silver/silver chloride electrode imbedded in the mounting and the scalp is ensured through the use of a firm, sponge-like material known as "Suca-Blok", a Swedish trade name. This material is saturated with 0.3 molar NaCl solution; in addition, electrode paste is applied to the tip adjacent to the scalp to ensure good electrical contact.

Figure 5-3. Helmet with electrodes placed for experimental run.



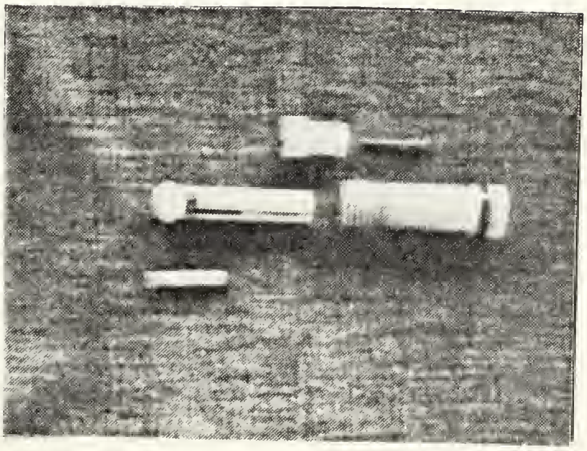


Figure 5-4. Electrodes assembled and disassembled.

D. FEEDBACK SUBSYSTEM

The feedback subsystem provides the interface between the computer and the light screen. It is a simple device which amplifies the updated feedback voltage received every 0.25 seconds and transmits this to the lamp behind the light diffusing screen. The console operator may visually monitor feedback level during a data run by observing a meter readout.

E. DATA DISPLAY UNITS

The flexibility of data display provided by display peripherals and display programs grants the experimentor great latitude in the selection of types of plots, scale factors, etc. Three pieces of equipment are involved with display and the PDP 11/40 controls two of them.

1. <u>HP-141B Four Trace, Storage Oscilloscope</u>

This excellent oscilloscope enables observation of the preamplified, filtered analog data before it is sampled. It is also used for testing of equipment. Abnormal noise, equipment problems and myograms are readily visible on this important display.

2. <u>Tektronix Storage Oscilloscope</u>

This unit is built into the console. It is controlled by the PDP 11/40 and processed digital data are displayed on it in real time or on reruns from disk storage. This display is closely monitored during all runs for indications of program malfunction, myograms or unusual noise indications.

3. <u>HP-7004B X-Y Recorder</u>

This unit, in conjunction with the PDP 11/40 program library, provides the hard copy of experimental results. It has great versatility and is a highly accurate device; however, plots are sometimes very time consuming. A line printer/plotter would be much more efficient for some types of plots.

VI. THE EXPERIMENTAL METHOD

There are two procedures required for completion of an experimental cycle. The first involves data collection and the attendant work with the equipment and the subject. The second is actual data manipulation by the experimentor with the PDP 11/40 utilizing the library of programs and subroutines available. Data collection and signal processing are real time, all handled by the particular program that is loaded. Raw or processed data may be stored on disk also as part of the real time cycle. The goal of these various procedures is to link the bandwidth under investigation with the measured performance criteria or activity.

A. DIGITAL SIGNAL PROCESSING AND TEGULOMETRIC ANALYSIS

1. Digital Signal Processing

The characteristics of the EEG lend themselves to digital signal processing techniques. The hardwired fast Fourier transform (FFT) incorporated in the F4 FFT Microprocessor by Time Data Corporation facilitates signal analysis of EEG data by meeting time constraints necessary for real time processing. The FFT is an efficient method for computing the discrete Fourier transform (DFT) of the time series data consisting of the discrete data samples derived from the analog to digital converter.

The DFT defines the spectrum of a time series. This time series completely defines the continuous waveform

assuming the waveform is frequency band-limited and the sampling rate is at least twice the highest frequency present in the waveform. The bandpass limitation for most experiments is set at 256 hertz, implying a Nyquist sampling rate of 512 samples per second for faithful reproduction of the continuous waveform.

The most useful aspect of the DFT for project purposes is to readily allow the accomplishment of ideal bandpass filtering. It is a simple matter of zeroing all complex spectral coefficients that are not in the bandpass of interest! The filtering is ideal in that there is no phase or amplitude distortion and the cutoff is very sharp provided certain precautions have been taken.

2. Tegulometric Analysis

The variable passband which results from the selective cancellation of DFT coefficients not of interest creates a very powerful analytical tool for EEG exploration. When ideal digital narrowband filtering techniques were first applied to the analysis of EEG's, it was seen that the inverse fast Fourier transform (IFFT) of the band limited waveform appeared as a waxing and waning sinusoid (Fig. 6-1). The period of this sinusoid is typically about 0.1 second and it is called......

" TEGULE" (emphasis added)

Hence, Tegulometric Frequency Analysis. References 14 and 17 contain considerably more detailed information on the development of this method.

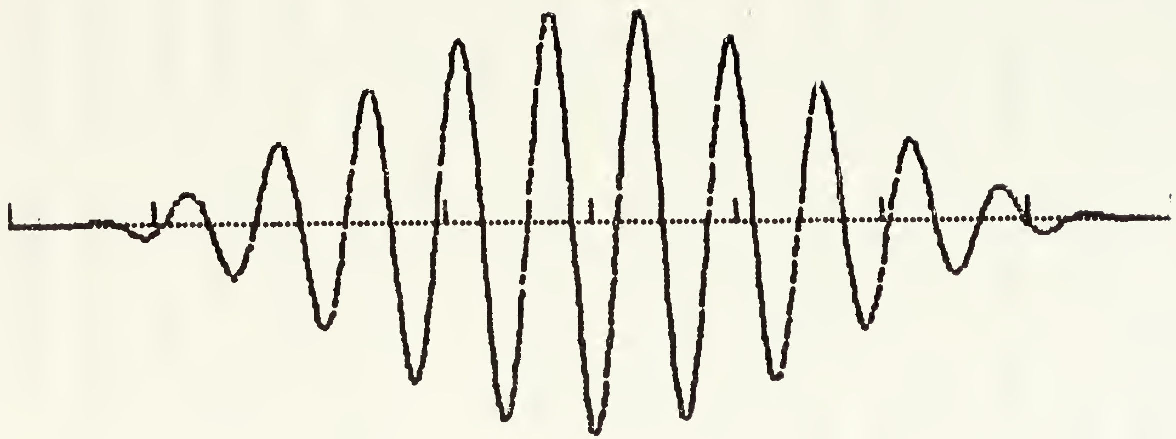


Figure 6-1. A TEGULE.

FIGURE 6-1. A WAVELET

Now, the actual tegulometric frequency analysis begins with the measurement of the time duration between negative and positive zero crossings. This measurement is accomplished for each negative to positive crossing. The individual periods which result are inverted and the resulting frequency is placed as a count in a word reserved in the histogram block stored in core memory. Before the counts are stored, they are weighted because lower frequencies will tend to have less zero crossings than higher frequencies.

If the process being observed is stationary, i.e., its statistical properties do not change with time, then the histogram will be a highly accurate representation of the probabilities that particular frequencies are in the passband. Within certain limitations, the relative count is an indicator of the percentage of time that the frequency component was present during the total time of observation. It is truly a probabilistic measure.

The advantage of this method for EEG work is obviously that the results do not depend on the power spectra of the discrete components involved. Because of this fact, tegulometric frequency analysis is ideally suited for EEG analysis and other low signal level, high noise applications. See Ref. 9 for more detailed information.

B. THE EXPERIMENTAL PROCEDURE

A short description of the experimental procedure will illustrate for the reader the extreme caution which is exercised by the laboratory team to ensure that essentially

noise free results are obtained. An experimental run consists of three interdependent parts: 1) subject and equipment preparation, 2) data taking, 3) computation and display of results.

1. Preparation

This is a crucial stage and if it is not executed carefully the run cannot be successful. Equipment must be turned for warm-up and checked to see that it is operating normally. Electrodes must be carefully checked before and after mounting on the subject's head. Programs must be called out and test runs executed with and without a subject to ensure no program generated noise is present. Record keeping preparations whould also be made at this time.

Figure 6-2 demonstrates electrode positions used for the majority of data runs. Use of the previously described helmet/electrode configuration ensures consistent placement from run to run. Both mastoids are grounded in order to electrically isolate cortical activity from electrocardio and other life function generated electrical activity in the body.

During the research, various electrode positions and combinations were attempted in order to determine the optimal placement and combination for good, consistent results. Figure 6-2 presents the location and the unipolar lead off technique which appeared to provide the most consistently strong, reproducible data. Electrodes 2 and 3 are referenced

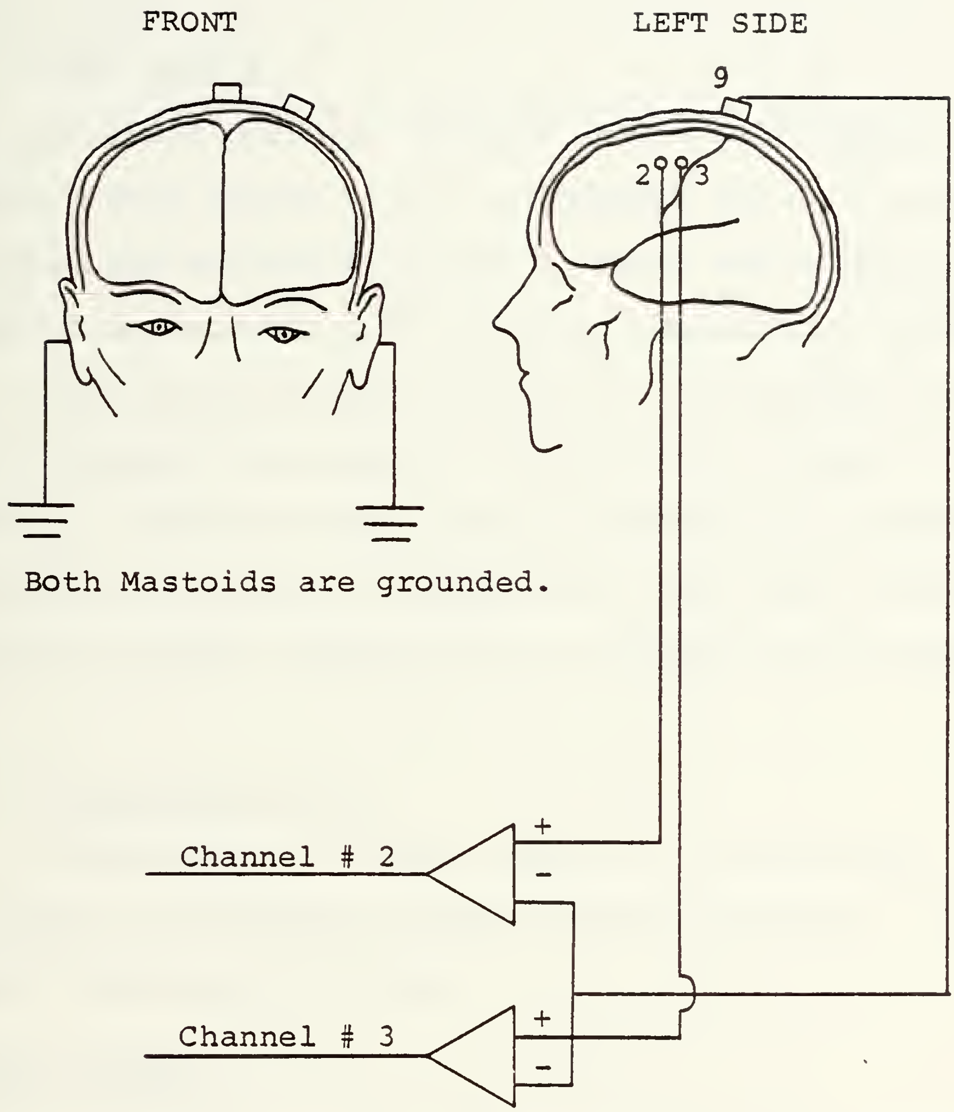


Figure 6-2. Unipolar referencing technique and location of electrodes for best results.

against electrode 9. This permits detection of activity directly under the two active electrodes which are only 7/8 inch apart.

2. Data Taking

Runs are typically divided into 6 X 100 second segments. This length of run is adequate for data without exhausting the subject's ability to relax and concentrate. It also allows flexibility for varying parameters between runs. A run might include 100 frames of the subject relaxed and not engaged in the task. This provides a baseline for comparison. Then the team normally gradually increases the difficulty of the task (increases the clock rate) while alternating between feedback and no feedback on different runs.

3. Data Manipulation

Examination of stored results is accomplished with the library of programs designed for this purpose. A more detailed explanation follows.

C. THE PROGRAMS

The program library is the foundation of the synchronous detection and data analysis techniques used by the laboratory team. There are two major classifications of programs; those utilized in data collection, and those used in data analysis. Attention will be confined to those programs actually used in this investigation. References 7, 14 and 16 contain additional information on these and others with possible application to this work.

1. TWODET

TWODET is the result of considerable past effort and it incorporates improvements in detection methods and programming techniques developed by the laboratory team. TWODET exists to enable identification of preferred frequencies.

Briefly, TWODET, as originally written, has the capability of taking the signals from eight electrodes and averaging them. This average can then be subtracted from the two closely spaced electrodes of interest whose signals are also included in the average. Note that it is not necessary to include this number of electrodes at all times. Figure 6-2 is an illustration of this. The beauty of TWODET is that it allows the experimentor a great deal of latitude in his selection of electrode positions and referencing schemes.

The subtraction of the average was deleted from the program and this seemed to enhance the results somewhat. The two resultant signals from electrodes 2 and 3 are then digitally bandpass filtered and cross multiplied. The result is a measure of the degree of correlation between the two signals.

Four types of data are stored on a disk by TWODET for later retrieval. They are: the processed data from channel 2, the processed data from channel 3, the cross multiplied correlation trace, and the performance indicator

trace from the tasking subsystem. Also, TWODET provides for real time display of this data while a particular run is in progress.

TWODET computes a cycle by cycle integration of the correlation trace. The updated values are converted to a voltage by the Digital Equipment Corporation Laboratory Peripheral System, and the voltage is sent to the feedback subsystem. Each feedback cycle is 0.25 second and each frame is 1.0 second.

The correlation trace provides the viewer with a real time opportunity to compare different types of activity as the run progresses. Details on the data traces will be provided in the data section of this paper.

2. <u>REPLAY- Series of Programs</u>

This group of display program enables the experimentor to select from a variety of display and printing options. Single frames or longer interesting segments may be printed or runs may be replayed repeatedly at different rates to enhance the viewer's perception of patterns or details of individual runs.

a. REPLAY.VAR

This program permits frame by frame viewing at different rates and includes a statistical plot of the entire run at the conclusion. Mean and standard deviation are plotted for each 100 frame segment.

b. REPLAY.PLT

Individual frames are plotted with this program after the disk address of the frame has been derived using REPLAY.VAR.

c. REPLAY.CPT

The experimentor can select desired sequences of data for plotting. Necessary parameters include starting disk address and number of frames to be plotted.

d. REPLAY.CON

It was decided that one of the problems with visual integration or interpretation of printed results is that too much data are sometimes presented and recognition of patterns by the experimentor is degraded. This problem was lessened considerably with the addition of a continuous averaging subroutine. This subroutine allows the viewer to select a time window of integration which tasks the PDP 11/40 and not the viewer with the problem of integrating minor deflections on the correlation trace. This technique enhances the larger, more predominant patterns.

e. REPLAY.CAV

This program is a natural extension of REPLAY.CON in that it permits plotting of continuous frames of data. There is an additional advantage in the plotting of a single line for the correlation plot rather than a line for each sample point. This saves considerable plotting time.

3. <u>HISCAN.EEG</u>

LCDR K. A. Tobin and Professor Marmont are engaged in a continuing investigation of the application of synchronous detection methods to anti-submarine warfare related problems. The analysis of undersea sonogram signals requires methods similar to those used for EEG analysis [Ref. 16].

HISCAN.EEG is a spin off from the old HISCAN program. The theoretical basis for tegulometric analysis is previously described in section VI A of this paper. Simply stated, the purpose of HISCAN.EEG is to determine, for a given run, the relative time during a given signal length that a particular frequency component occurs. This point is worth emphasizing once again; the plot is based on the time duration that the frequency component is present, <u>not</u> its amplitude.

The results of analysis of disks of wideband data are presented in the next section.

VII. DATA AND RESULTS

A. GENERAL

As stated at the outset, the goal of this thesis project is to establish the existence of a preferred frequency bandwidth in the EEG associated with the previously described subject task. The initial investigation was not entirely without guidance.

Reference 7 contains considerable information gathered during a recent laboratory investigation utilizing a Heads Up Display (HUD) from an F-111 aircraft. The author of Ref. 7 reports on the experimentally established fact that beginning around 60 Hz, and continuing as high as 200 Hz in some individuals, there is a significant increase in activity while the subject is engaged in a task which requires skill and attention. The author continues by reporting that further investigation established that 70-90 Hz appeared to be a particularly promising region because of the great increase in correlation while flying the HUD. In addition, Ref. 7 includes results of broadband EEG searches accomplished with the subject actively engaged in flying the HUD.

Data for the present investigation was gathered over a period of several months utilizing members of the laboratory team, the author included, as subjects. There are several reasons for limiting the subjects to those individuals

familiar with the project. Experience has demonstrated more consistent results are derived from well trained subjects. The trained subject is familiar with the environment and this enables him to relax and concentrate more completely. Relaxation is absolutely essential when broadband searches are being conducted to preclude contamination by myograms. Also, it has been experimentally observed that the attitude of the subject toward the experiment has significant impact on the results. The task is somewhat difficult to execute properly over a run and the subject's willingness to "put out" has a great effect on results. The subject cannot sit passively and react; the experiment requires active interaction with the equipment for the entire run. Subject comments indicated a high degree of correlation between good data runs and the personal feeling of the subject that performance had been good.

B. THE INVESTIGATION

Investigation and data collection centered in the 30-55 Hz and 70-95 Hz regions of the EEG. Previous results indicated that 70-95 Hz would be more production; however, 30-55 Hz was also covered to satisfy the team that the search was concentrating on the correct frequency band. The investigation at 30-55 Hz did not give promising results and the investigation shifted to the previously described 70-95 Hz region.

After it was decided 70-95 Hz provided optimal results in terms of heightened patterns of response to the task as measured on the correlation trace; various efforts were made to further refine the technique by changing electrode positions and referencing schemes. The optimal configuration for this task was determined to be as pictured in Figure 6-2. Data presented here are derived from this electrode setup.

In addition, broadband data are presented which were obtained from the above mentioned electrode setup. These data are particularly interesting in that they confirm previously reported results and support experimental results derived from TWODET during the present investigation. This will be discussed in detail in the results section of this report.

C. DATA PLOTS

Data are divided into three major categories: 1) TWODET experimental run plots with filtered EEG and performance data; 2) REPLAY.VAR statistical plots of levels of correlation for various runs; 3) HISCAN.EEG plots demonstrating the broadband frequency histograms for experimental activities without feedback enhancement.

1. TWODET- Experimental Plots

These results are divided into three subsections: 1) relaxed, eyes open, no feedback; 2) slow clock (1.8 Hz); 3) fast clock (4.0 Hz).

In addition, the difference between runs with and without visual feedback will be emphasized.

a. Relaxed, No Feedback, Eyes Open

Figures 7-1 to 7-4 provide a baseline for comparison to activity levels presented in later plots. These plots are selected because they present a variety of tegule characteristics typical of the relaxed state with eyes open. The amount of correlation between channels 2 and 3 is slight and pulses of positive and negative correlation appear to be random and unassociated. Figure 7-4 is very interesting because the heightened level of activity on channel 3 does not lead necessarily to increased correlation.

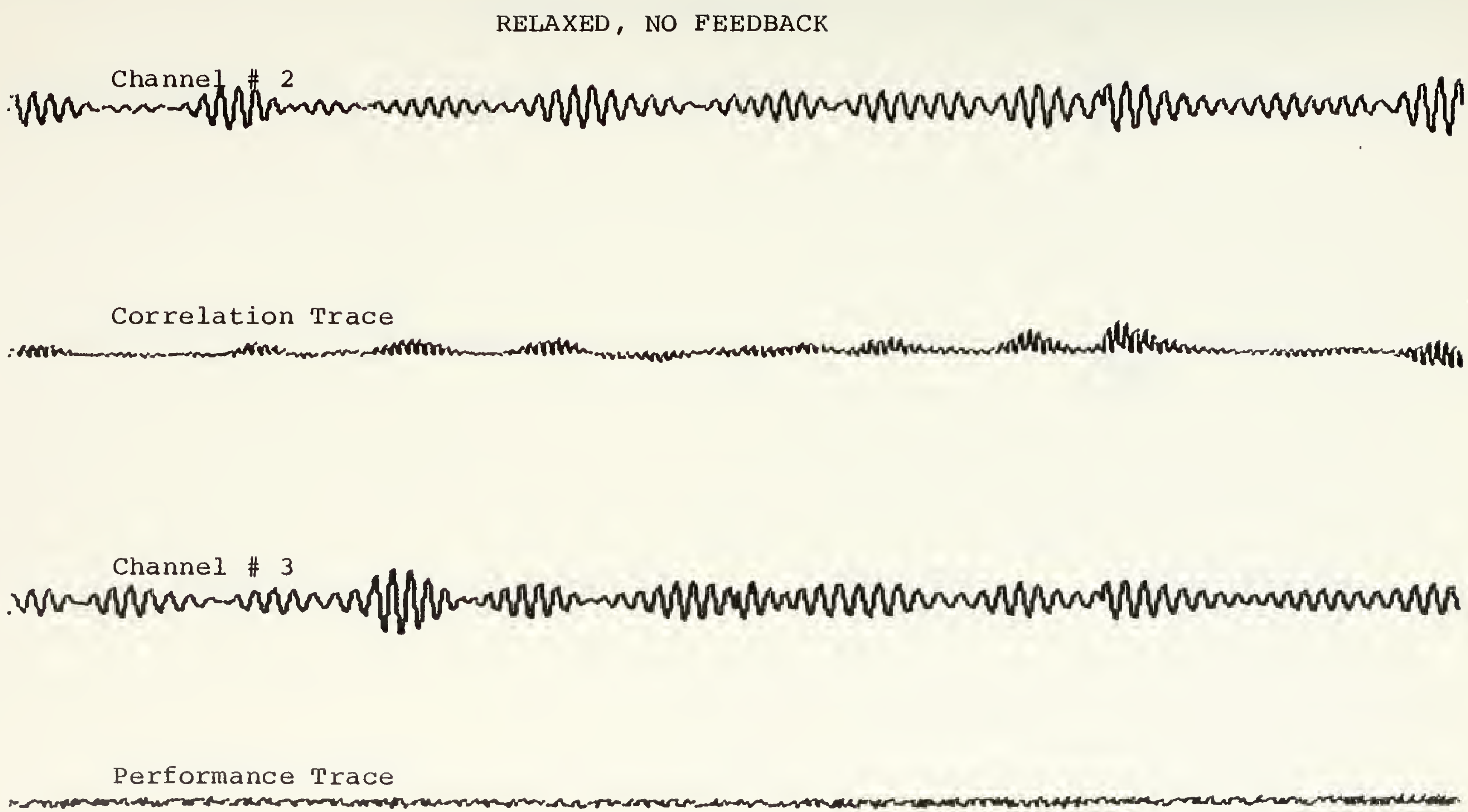


Figure 7-1. Relaxed, No Feedback, 70-95 Hz.

RELAXED, NO FEEDBACK

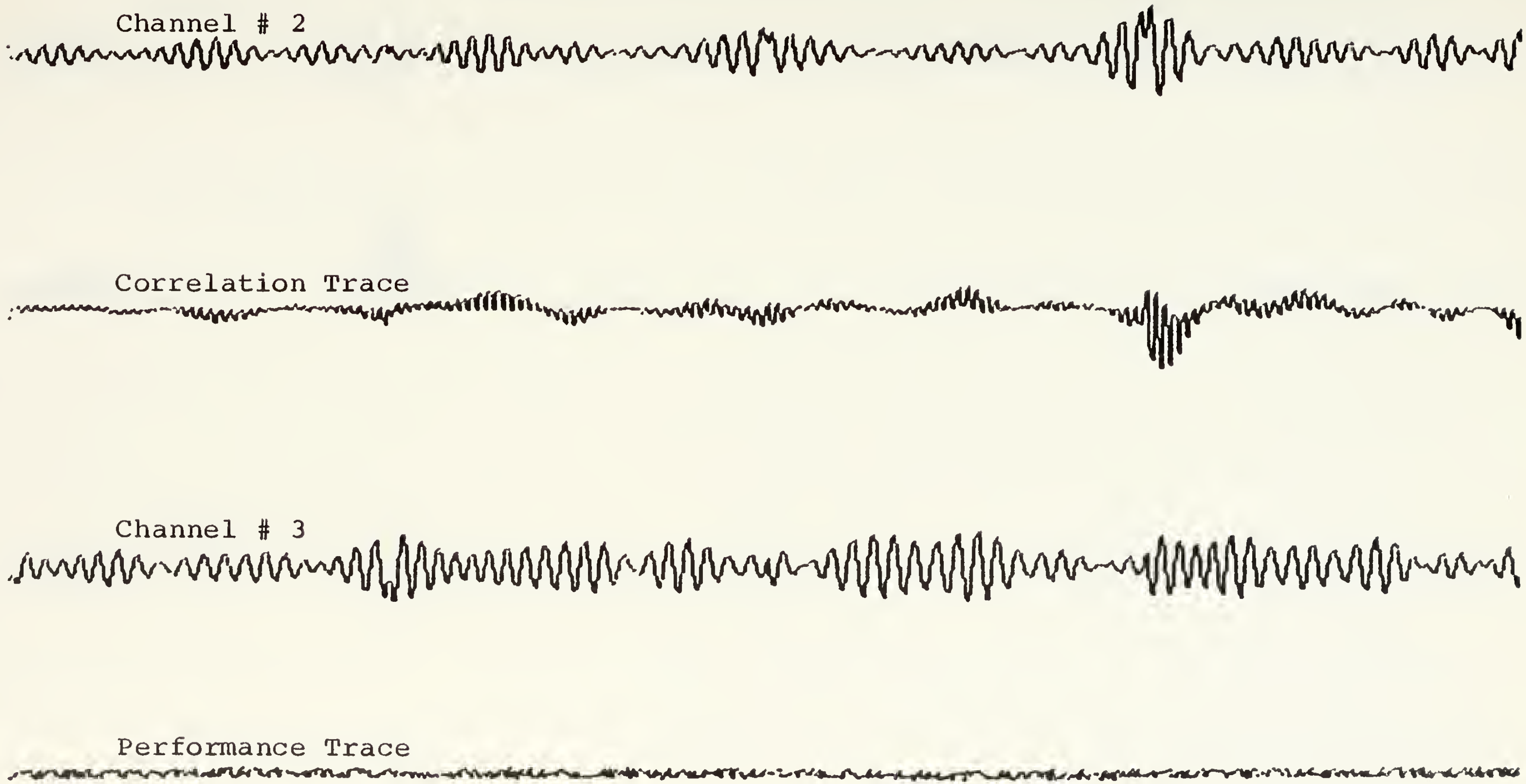


Figure 7-2. Relaxed, No Feedback, 70-95 Hz.

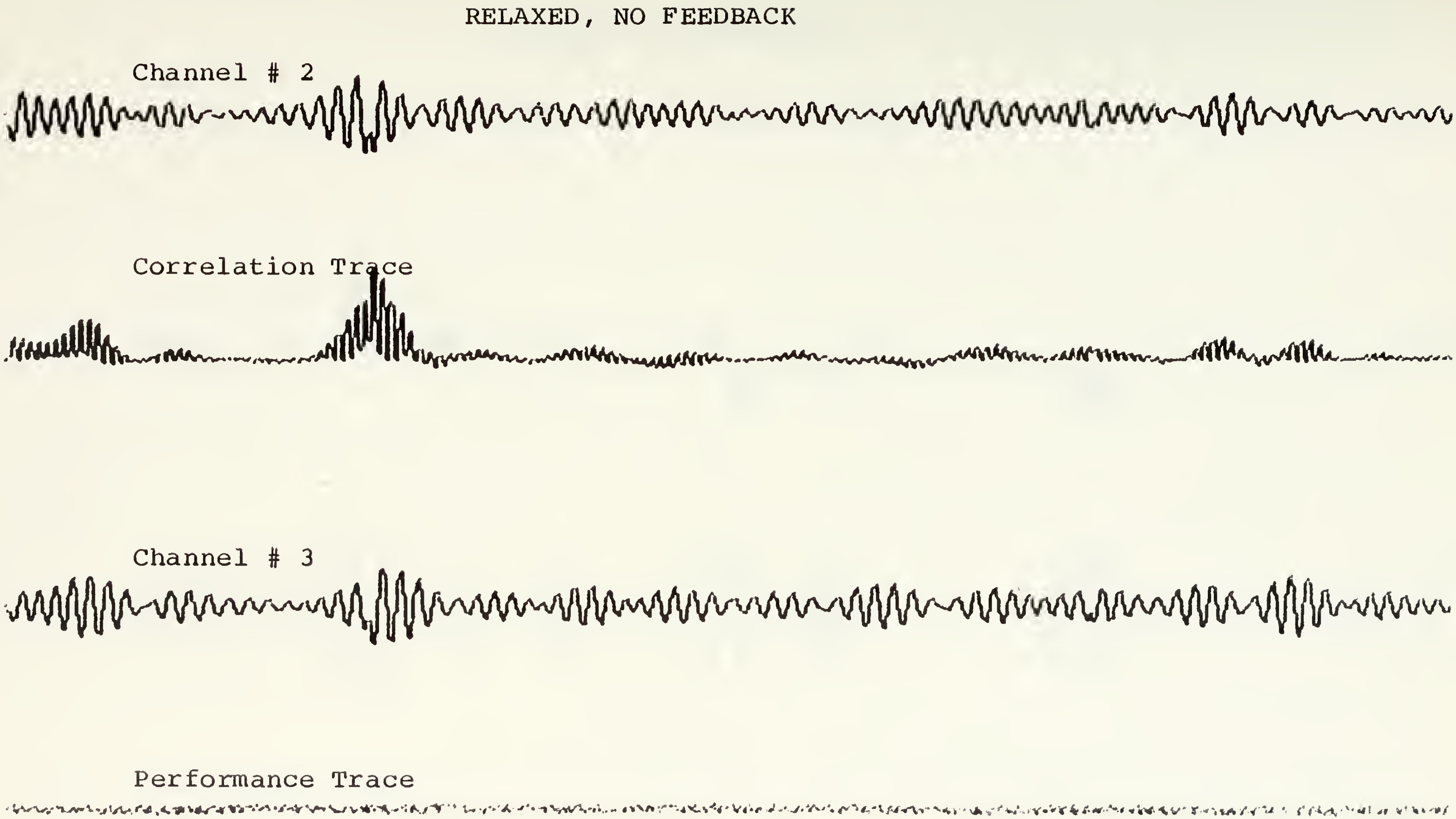


Figure 7-3. Relaxed, No Feedback, 70-95 Hz.

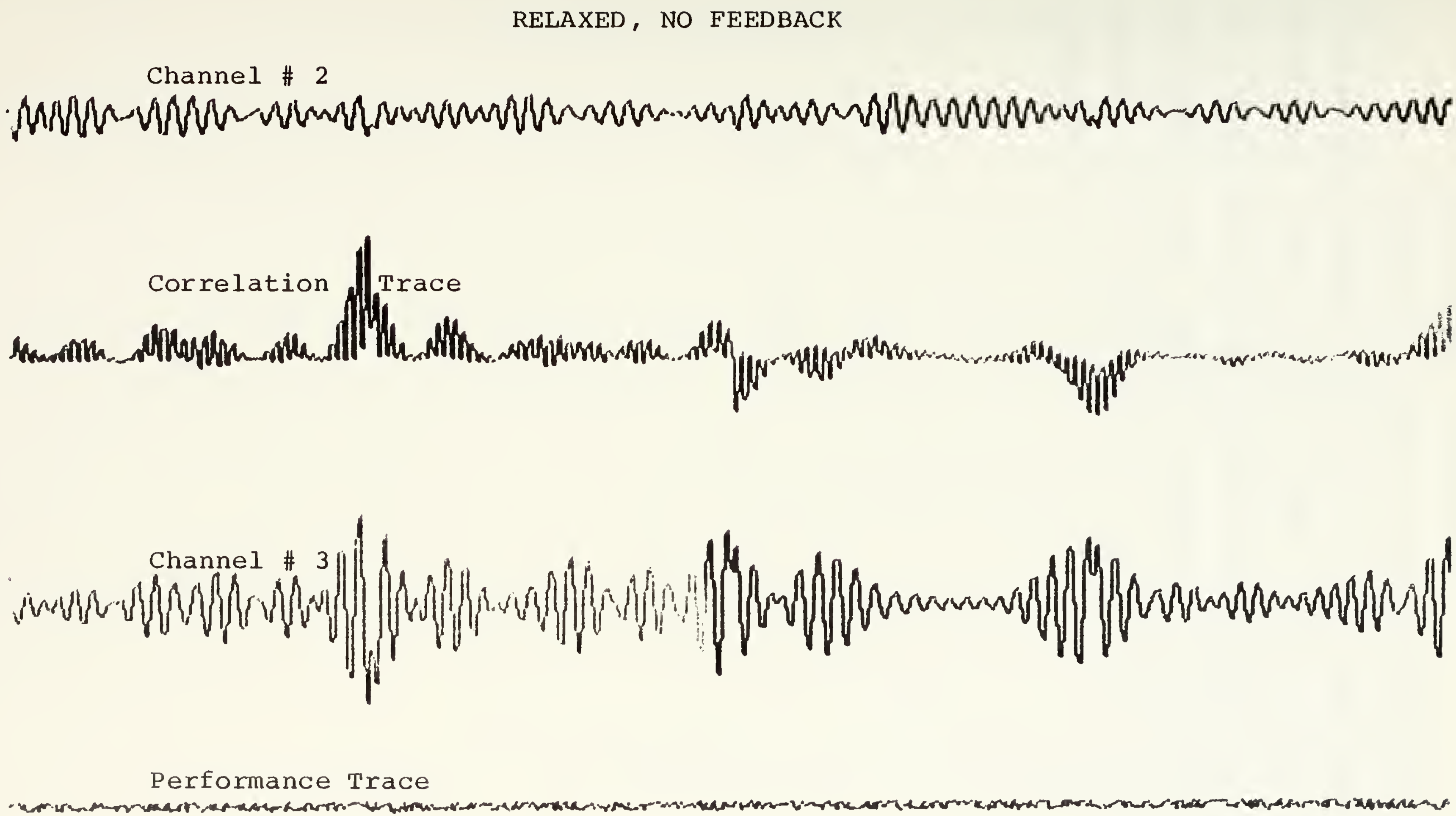


Figure 7-4. Relaxed, No Feedback, 70-95 Hz.

b. Slow Clock, No Feedback

Figures 7-5 and 7-6 are good examples of correlation patterns elicited by single disturbances of the CRO dot viewed by the subject. Note in particular how the tegular activity has become more similar between electrodes 2 and 3 and the increase in correlation as compared to the relaxed state. Feedback has not yet been introduced.

SLOW CLOCK, NO FEEDBACK

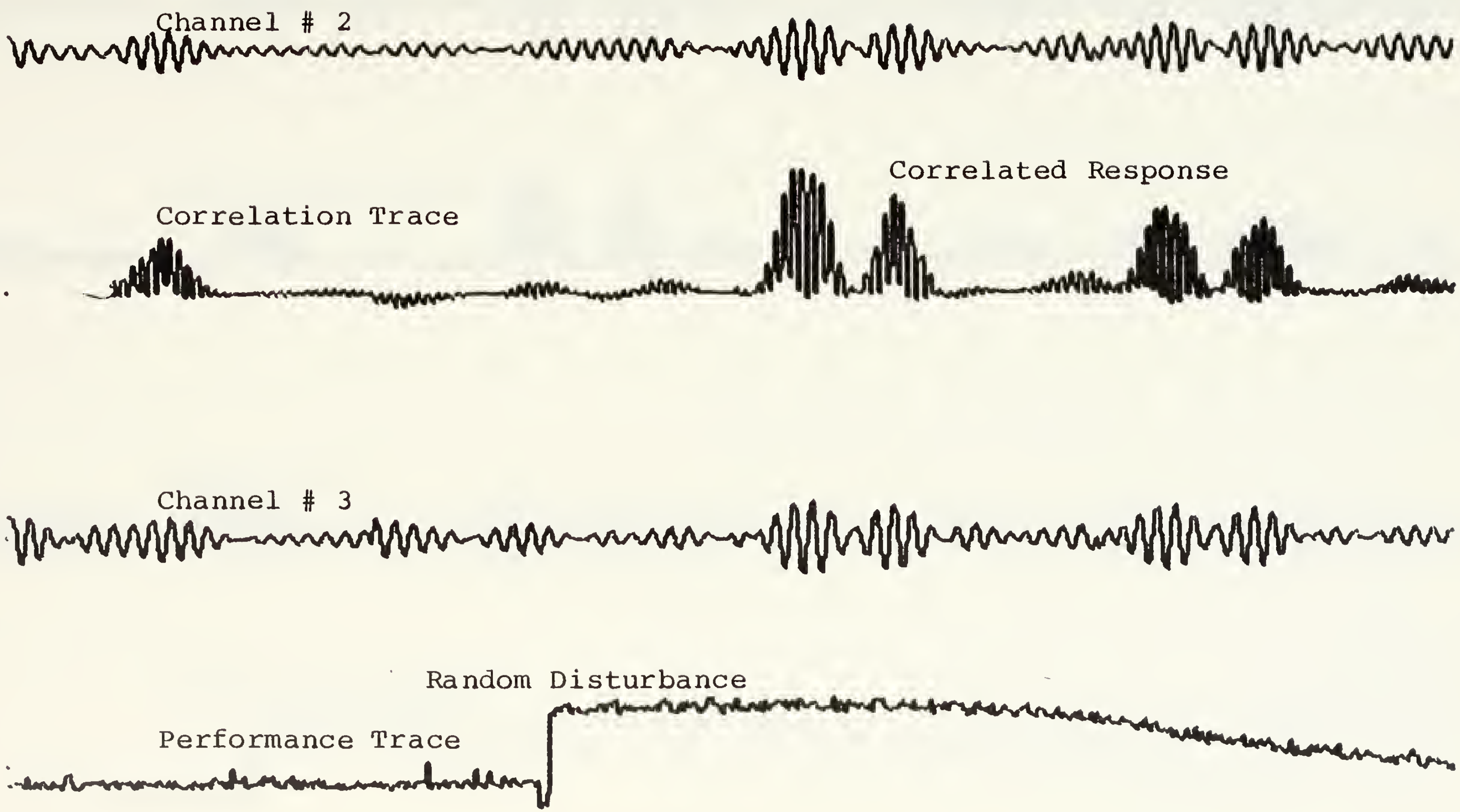


Figure 7-5. Slow Clock, No Feedback, 70-95 Hz.

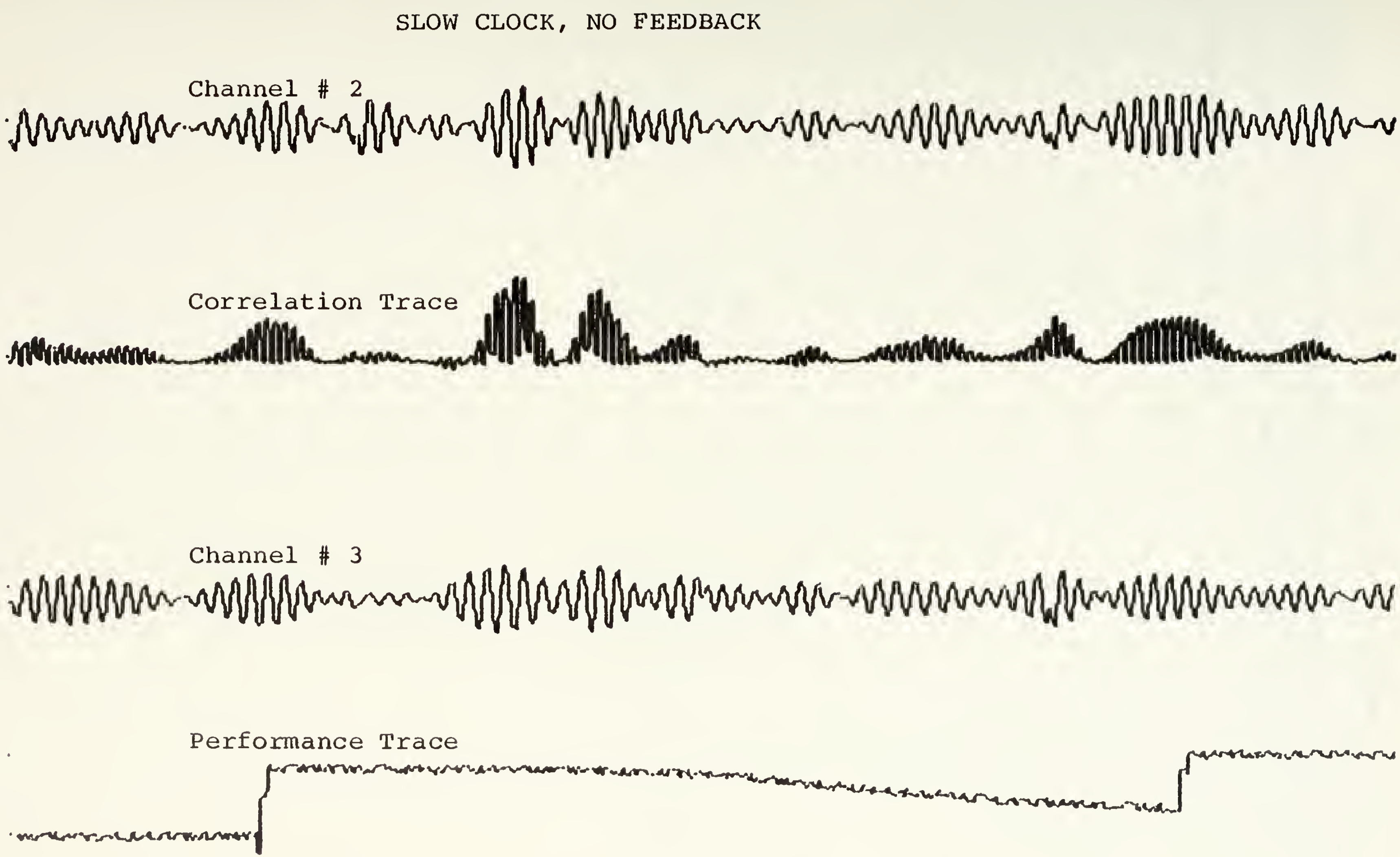


Figure 7-6. Slow Clock, No Feedback, 70-95 Hz.

c. Fast Clock, No Feedback

Figure 7-7 shows a great increase in positive correlation as the response from one pulse is superimposed on another. Note again the high degree of similarity between the tegule plots.

FAST CLOCK, NO FEEDBACK

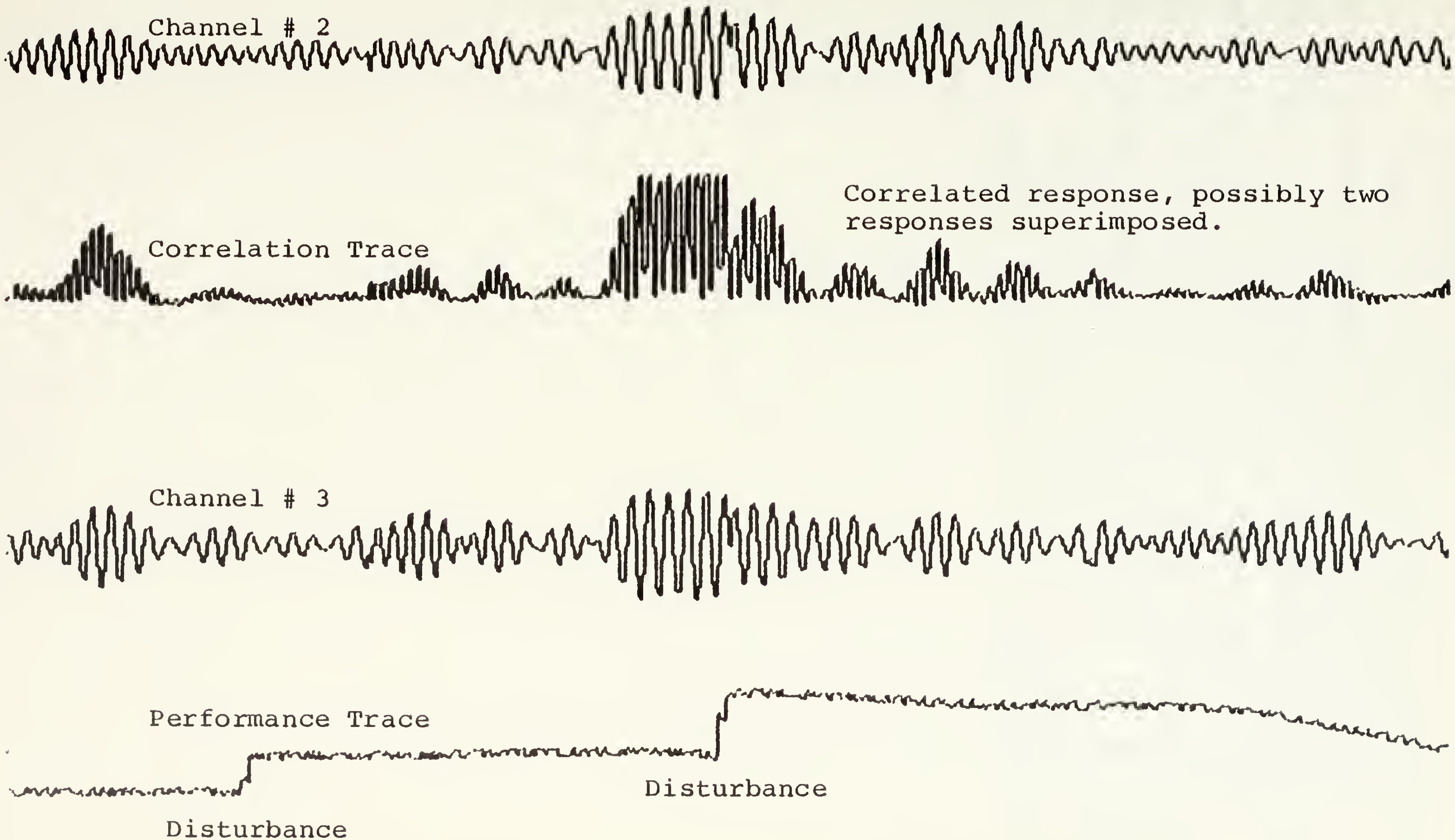


Figure 7-7. Fast Clock, No Feedback, 70-95 Hz.

d. Fast Clock, Feedback

Figures 7-8 through 7-12 show the pattern of correlation which has been observed repeatedly during tasked data runs with feedback. The patterns are characterized by groups of four or five peaks about 0.1 sec apart. The statistical significance of these patterns as compared to the remainder of the run has yet to be quantified.

Figures 7-11 and 7-12 show two sequential frames that are a graphic demonstration of the reproducibility of these results.

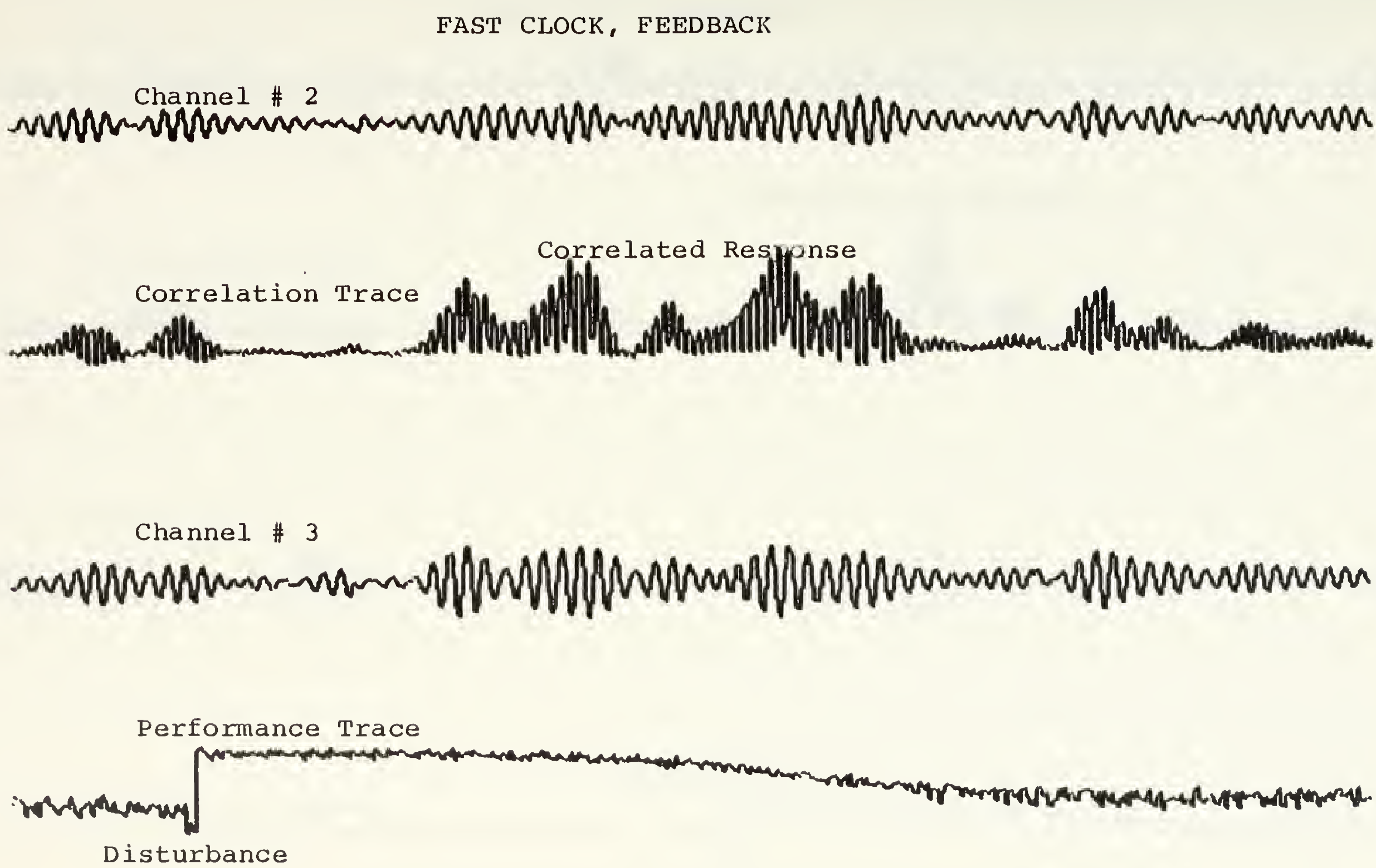


Figure 7-8. Fast Clock, Feedback, 70-95 Hz.

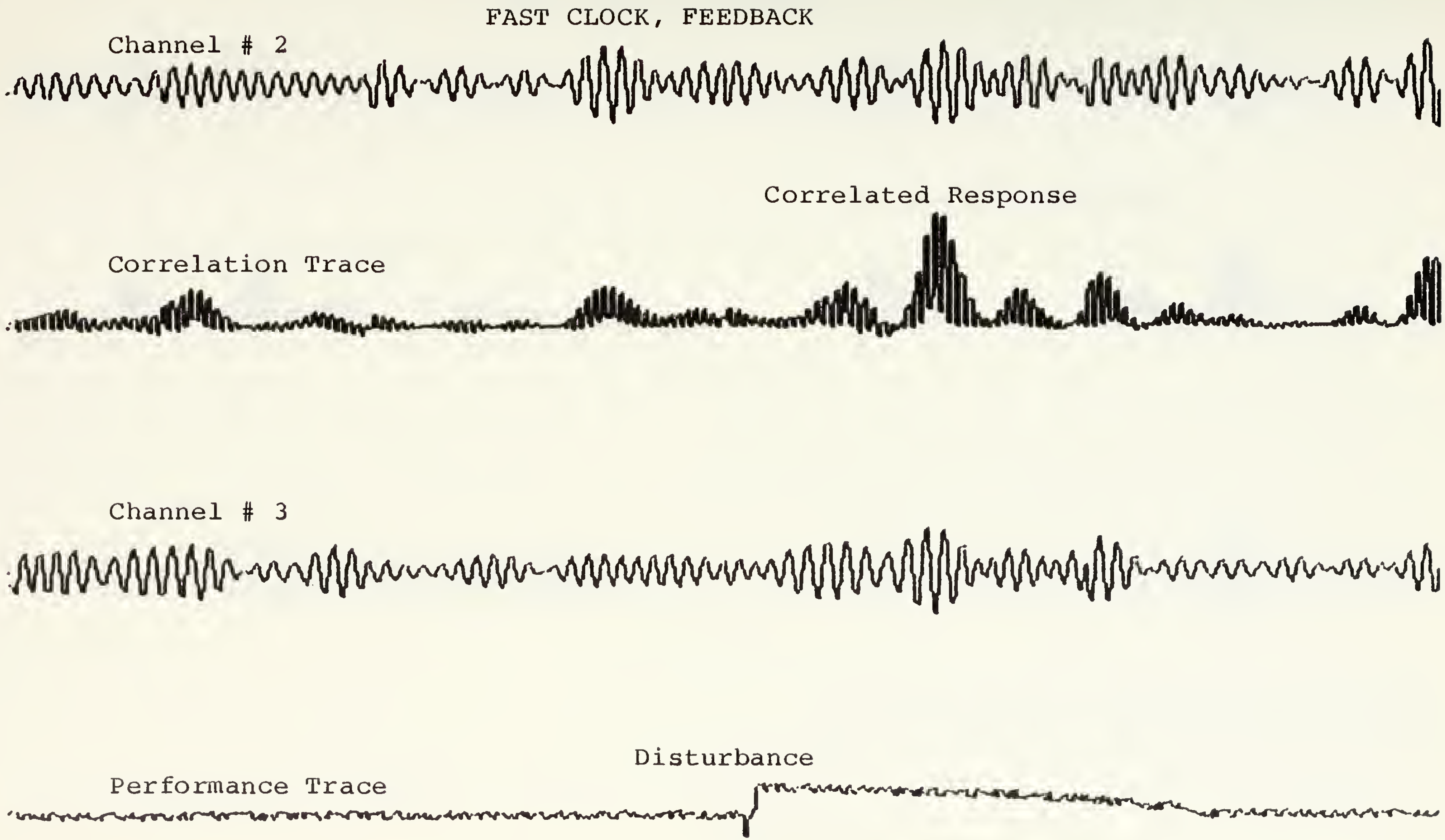


Figure 7-9. Fast Clock, Feedback, 70-95 Hz.

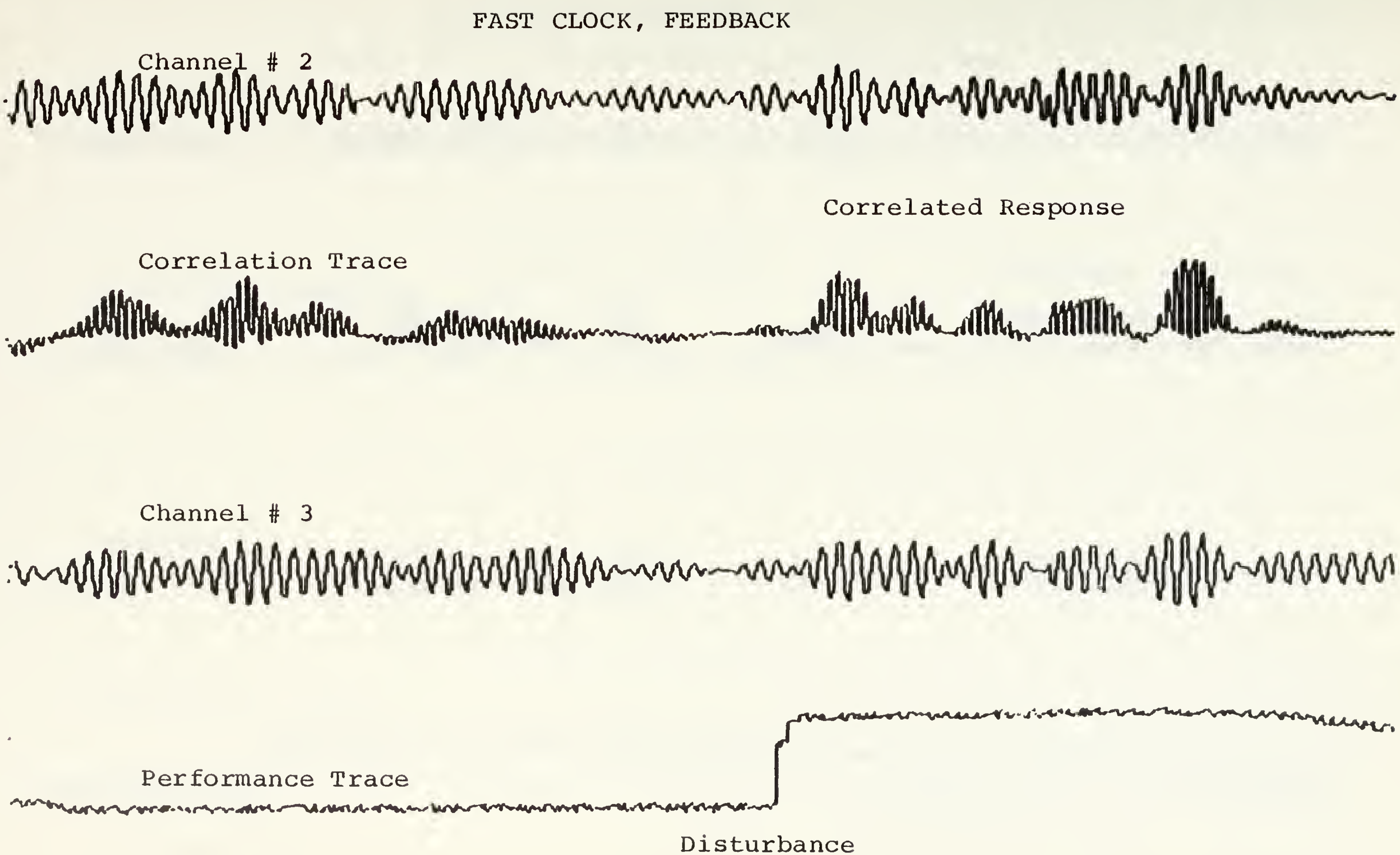


Figure 7-10. Fast Clock, Feedback, 70-95 Hz.

FAST CLOCK, FEEDBACK

(Fig. 7-12 is a continuation of this frame)

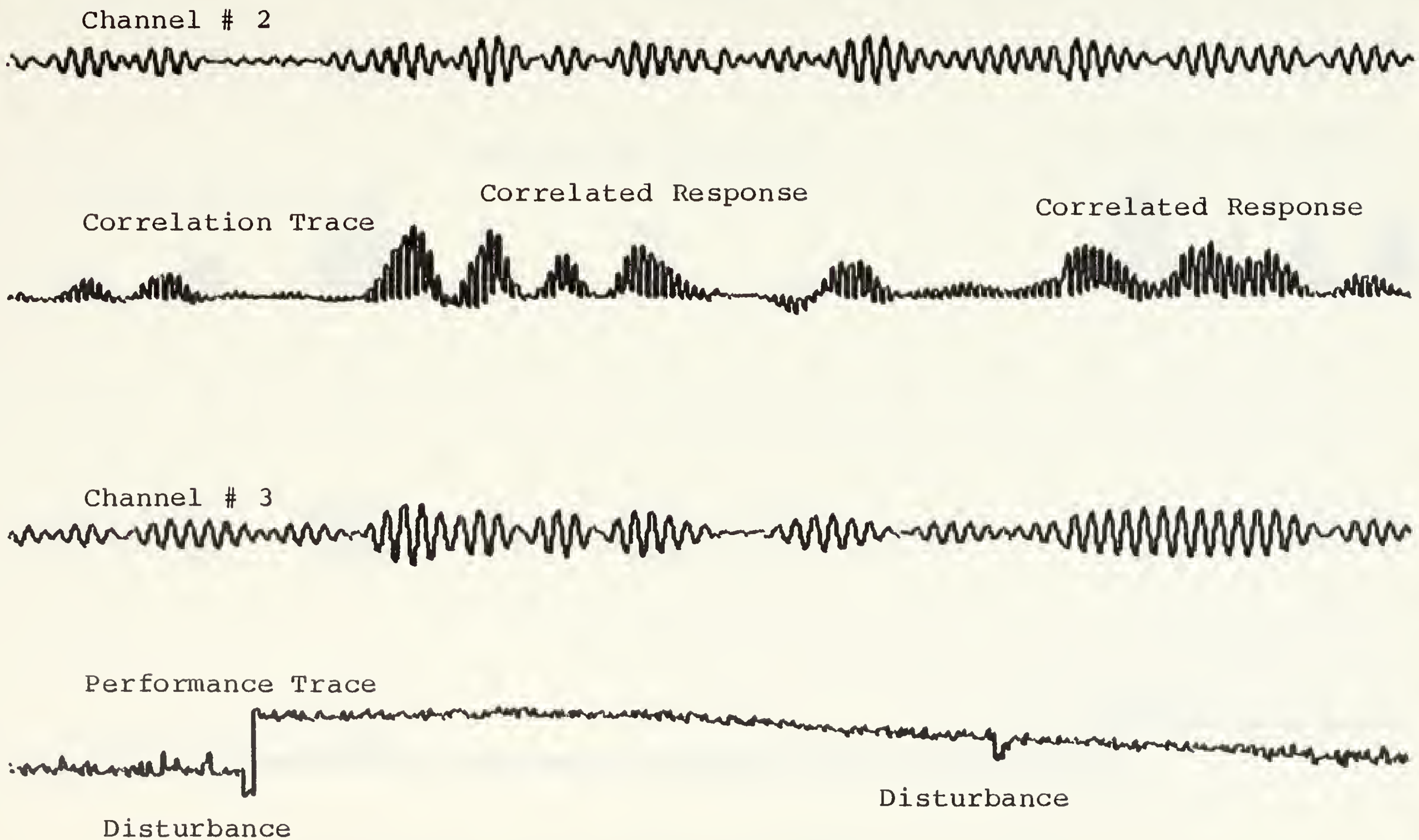


Figure 7-11. Fast Clock, Feedback, 70-95 Hz.

FAST CLOCK, FEEDBACK

(This is a continuation of Fig. 7-11)

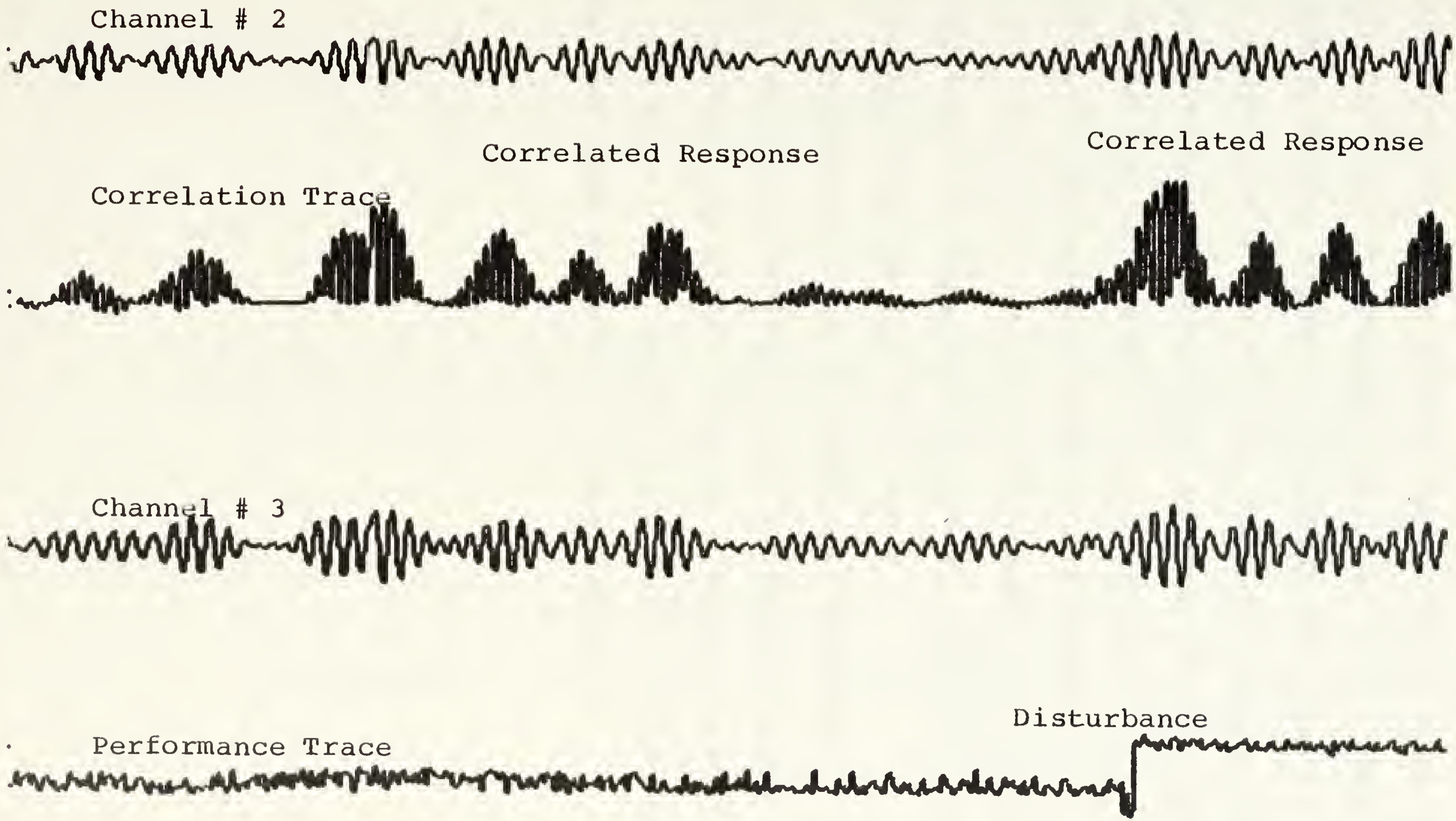


Figure 7-12. Fast Clock, Feedback, 70-95 Hz.

2. REPLAY.VAR- Statistical Plots

This display of processed data is very useful for deciding which part of a particular series of runs shows the most potential of promising results. The statistical plots are an option added to the REPLAY.VAR program.

Figures 7-13 and 7-14 are included because they show the significant increase in correlation which occurs with the addition of feedback as a stimulus to the subject. The plots are from different subjects engaged in the same sequence of activity. The scale factors for the plots are also identical for comparison purposes. Note how the trends in subject performance are identical.

Feedback enhances the amount of positive correlation for both subjects as evidenced by the higher average correlation shown on the plots. This is a typical result.

The lines drawn on the plots indicate the mean and standard deviation for each 100 frame segment.

REPLAY.VAR STATISTICAL PLOT

Note: Each segment is 100 frames or 100 seconds. The lines on each segment represent mean and standard deviation. 600 seconds of data are represented.

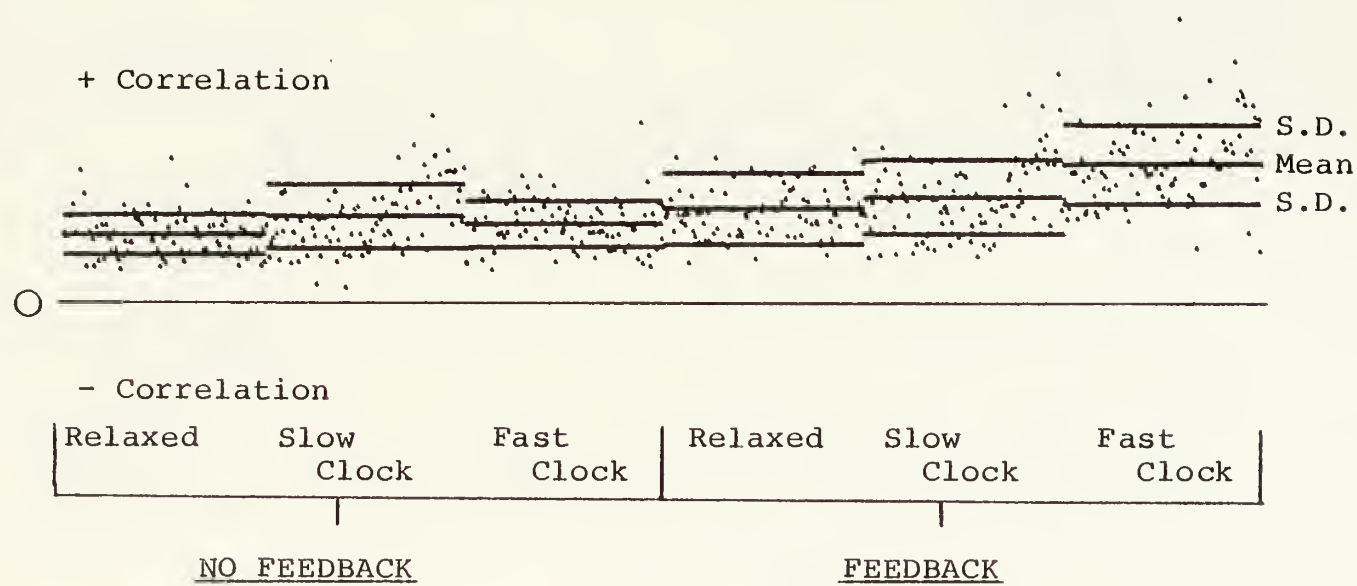


Figure 7-13. REPLAY.VAR Statistical Plot.

REPLAY.VAR STATISTICAL .PLOT

Note: Each segment is 100 frames or 100 seconds. The lines on each segment represent mean and standard deviation. 600 seconds of data are represented.

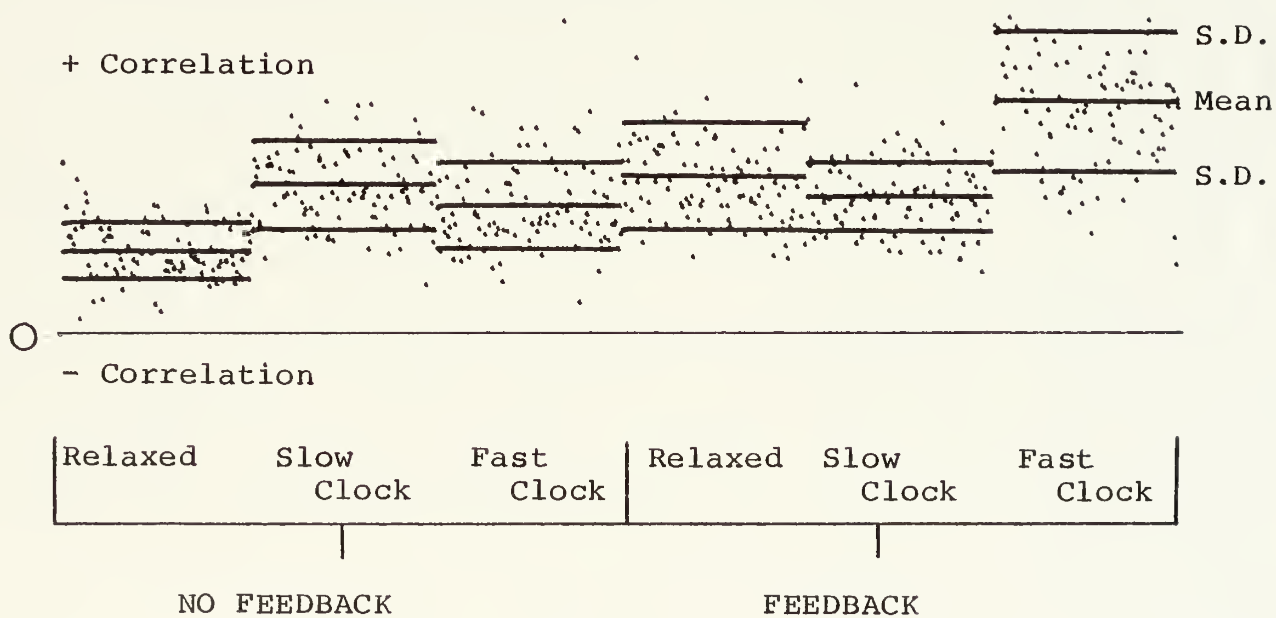


Figure 7-14. REPLAY.VAR Statistical Plot.

3. <u>HISCAN.EEG- Probability Density Plots</u>

Figures 7-15 and 7-16 demonstrate that there are distinct frequencies in the passband of interest which show prevalence from a probabilistic standpoint. The TWODET experimental bandwidth is clearly marked.

One predominant peak is typically located in the 78-81 Hz region and another occurs around 90 Hz. These plots reinforce TWODET data already presented and they support results previously reported in Ref. 7.

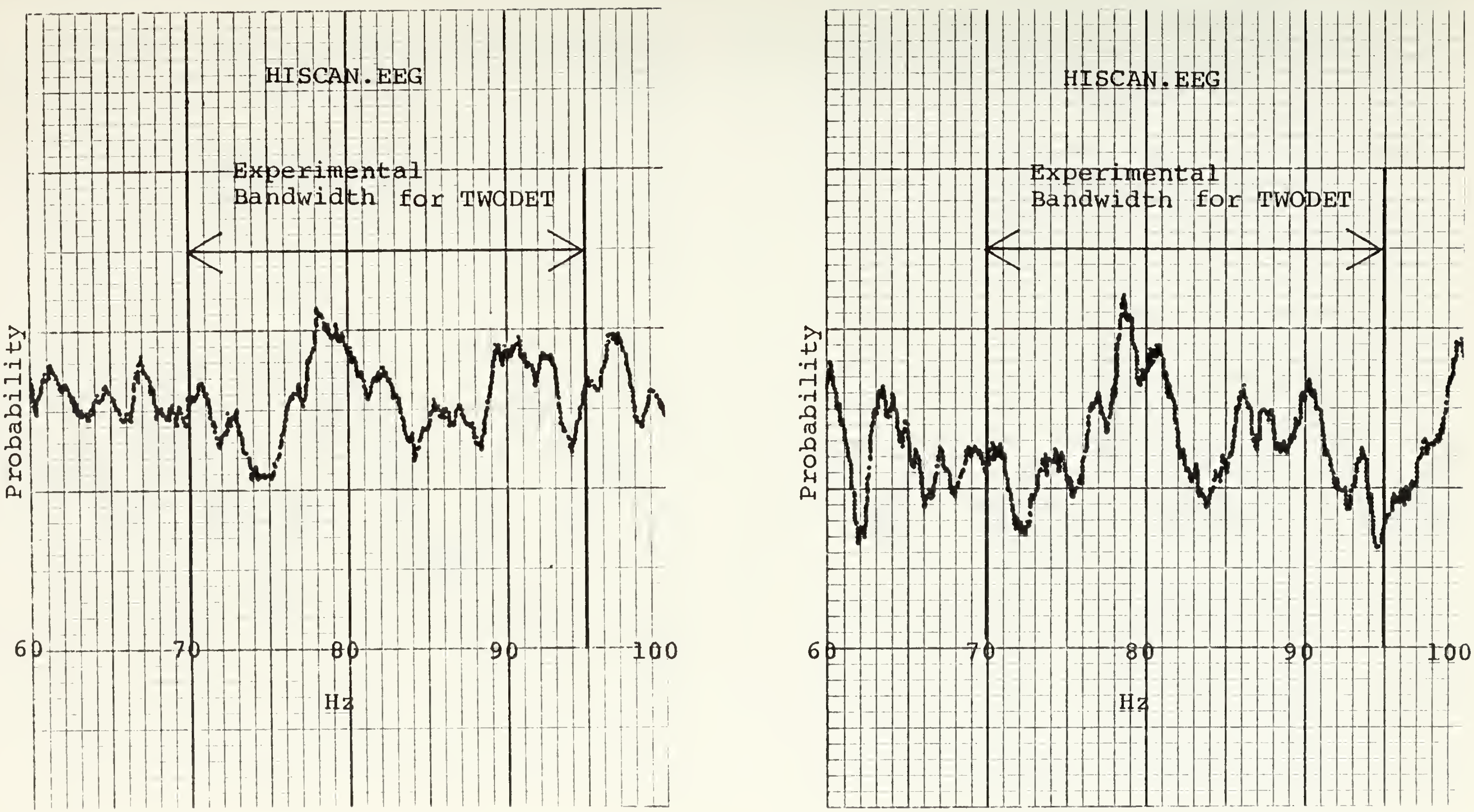
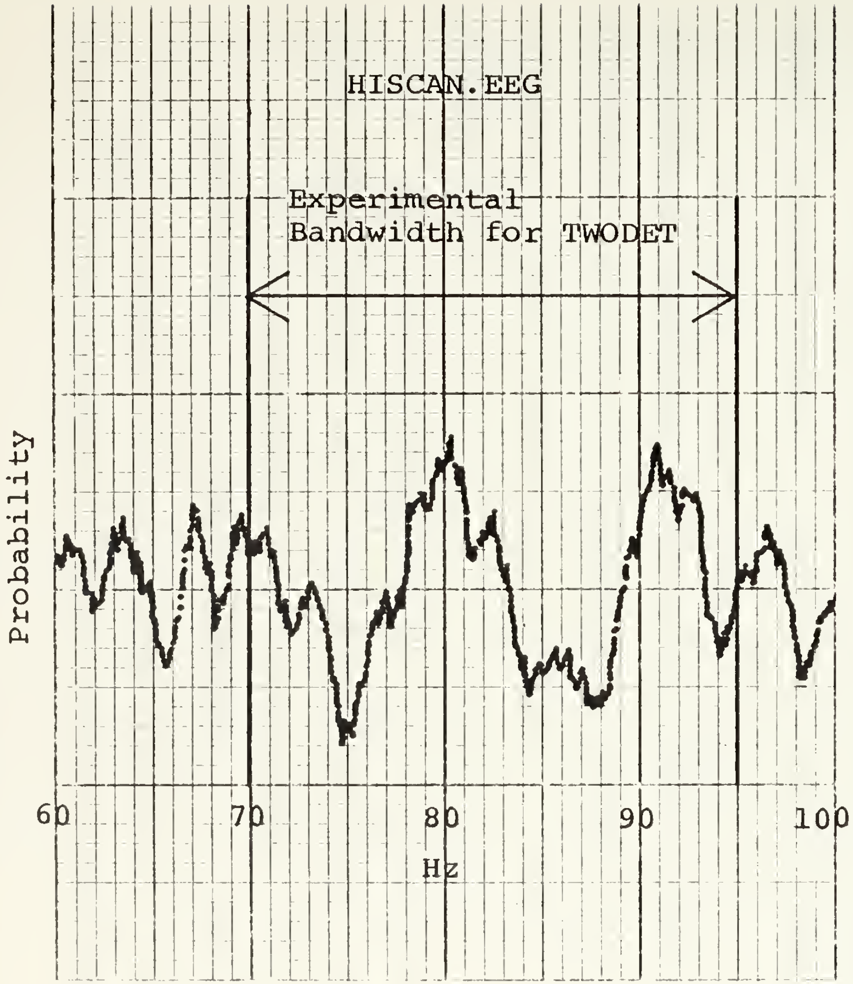


Figure 7-15. HISCAN.EEG Probabilistic Plots.



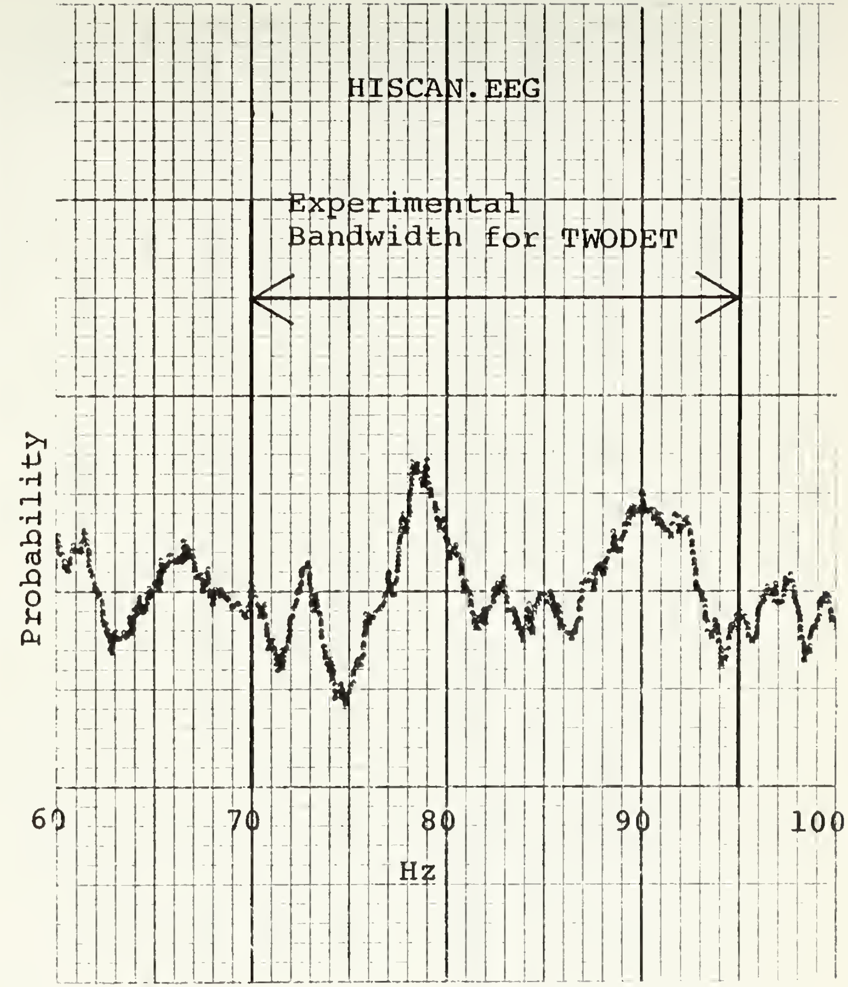


Figure 7-16. HISCAN.EEG Probabilistic Plots.

D. RESULTS

1. General

Several months of intensive use have proven the tasking subsystem to be reliable and adequate for the requirements of the investigation. The helmet and electrodes provide flexibility of scalp access and reproducibility of position.

The introduction to the data section provides background information on prior results which suggested possible starting points for this investigation. The recommendation on bandwidth of interest presented in Ref. 7 appears to be valid. All subjects tested had superior results in the 70-95 Hz region versus the 30-55 Hz bandwidth. HISCAN.EEG data also support the data presented in Ref. 7.

Electrode positioning is one of the most sensitive areas of investigation. Deviation from desired placement by as little as one centimeter can completely alter results. Selection of reference position and configuration is vitally important. A single electrode placed on the vertex in close proximity to the two active alectrodes produced optimal results.

Some unusual combinations of electrodes were tested. One pattern included all available electrodes, except for the two active electrodes, shorted together and arranged in a circle about the area of interest. It was hoped this referencing scheme would provide a greater reduction of noise by averaging out all neural activity surrounding the

experimental electrodes. The technique failed, however, when it became obvious the desired signals were being suppressed also.

A significant amount of effort was expended testing orientation of the two active electrodes. Electrode 2 was left in place as a constant, and electrode 3 was moved in its immediate vicinity. One of the most significant findings of the investigation resulted. As long as electrode 2 and electrode 3 were located perpendicular to the central sulcus (Fig. 6-2), results were good. When their orientation became parallel to the central sulcus results were degraded considerably. Recalling Fig. 3-5, the functional arrangement of the motor/premotor area is columnar with sections ranked vertically by area of the body. What is suggested by these results is that when electrodes 2 and 3 are perpendicular to the central sulcus, they are engaged in measuring the same activity, as evidenced by the increase in positive correlation. When electrodes 2 and 3 are parallel to the central sulcus, they are probably located in different functional areas, so naturally the amount of correlation decreases. This result was found to be true without exception.

Experimental results show a correlation pattern connected with the experimental task in the 70-95 Hz area. The pattern is normally characterized by four or five peaks spaced about 0.08 to 0.12 sec apart which follow the inverted

marker on the performance trace which shows the start of a disturbance. The data plots give ample demonstration of this phenomenon. It is not yet known in a quantitative sense whether the pattern is statistically significant as compared to the activity on the remainder of the experimental run. A program is now being developed to pursue the question of statistical significance.

The results of the HISCAN.EEG wideband investigation (4-220 Hz) lend support to previous results [Ref. 7] and also provide the team with an additional display tool for future investigations.

2. Summary of Results

Results are summarized here, for clarity, in outline form. TWODET results are as follows:

a. There is a greater degree of correlation between electrodes 2 and 3 at 70-95 Hz than at 30-55 Hz.

b. Electrode positioning and orientation of electrodes 2 and 3 are very important. Referencing of the active electrodes to the vertex produces optimal results.

c. The correlation patterns associated with the experimental task can be characterized as consistently occurring groups of four or five peaks which are significantly greater in amplitude than the activity on the remainder of the trace.

d. Visual feedback enhances the amount of positive correlation present when the subject is engaged in a task.

HISCAN.EEG results are summarized below:

e. There are distinct frequencies which show prevalence, from a probability standpoint, over the frequency band of interest. The histogram, which is a true frequency probability density function, shows not only that certain frequencies are prevalent, but the similarities between histogram plots are very close for task related data.

f. It is certain that myograms and extraneous noise sources are not responsible for these patterns.

g. It is significant that in the 70-95 Hz region, there is a sharp peak close to or at 79 Hz. Also, at 90 Hz there is a sharp but variable peak.

One can conclude that increased tegular activity in the 70-95 Hz range found with TWODET is directly related to the twin peaks seen in this range with the HISCAN.EEG analysis. This can be verified by measuring the frequency composing associated tegules where there is a high degree of task related correlation.

Figure 7-17 shows a section of plotted TWODET data. The frequency is measured over the range of the tegule as indicated in the figure. The frequency in the figure measures 80.9 Hz as the average for the .227 sec measured. Other similar results are shown in Table 7-1. This is a strong verification of the connection between the TWODET data and the HISCAN.EEG plots. The results of Table 7-1 are not due to the "pulling" of frequencies in the filtered band. Pulling toward the center frequency of the filtered

band occurs when two or more frequency components of similar amplitude beat. It has been demonstrated by earlier records where frequency of the tegules were measured that the frequencies ranged the whole filter band unless beating occurred. However, beating can be quite easily recognized and did not occur in data used in Table 7-1.

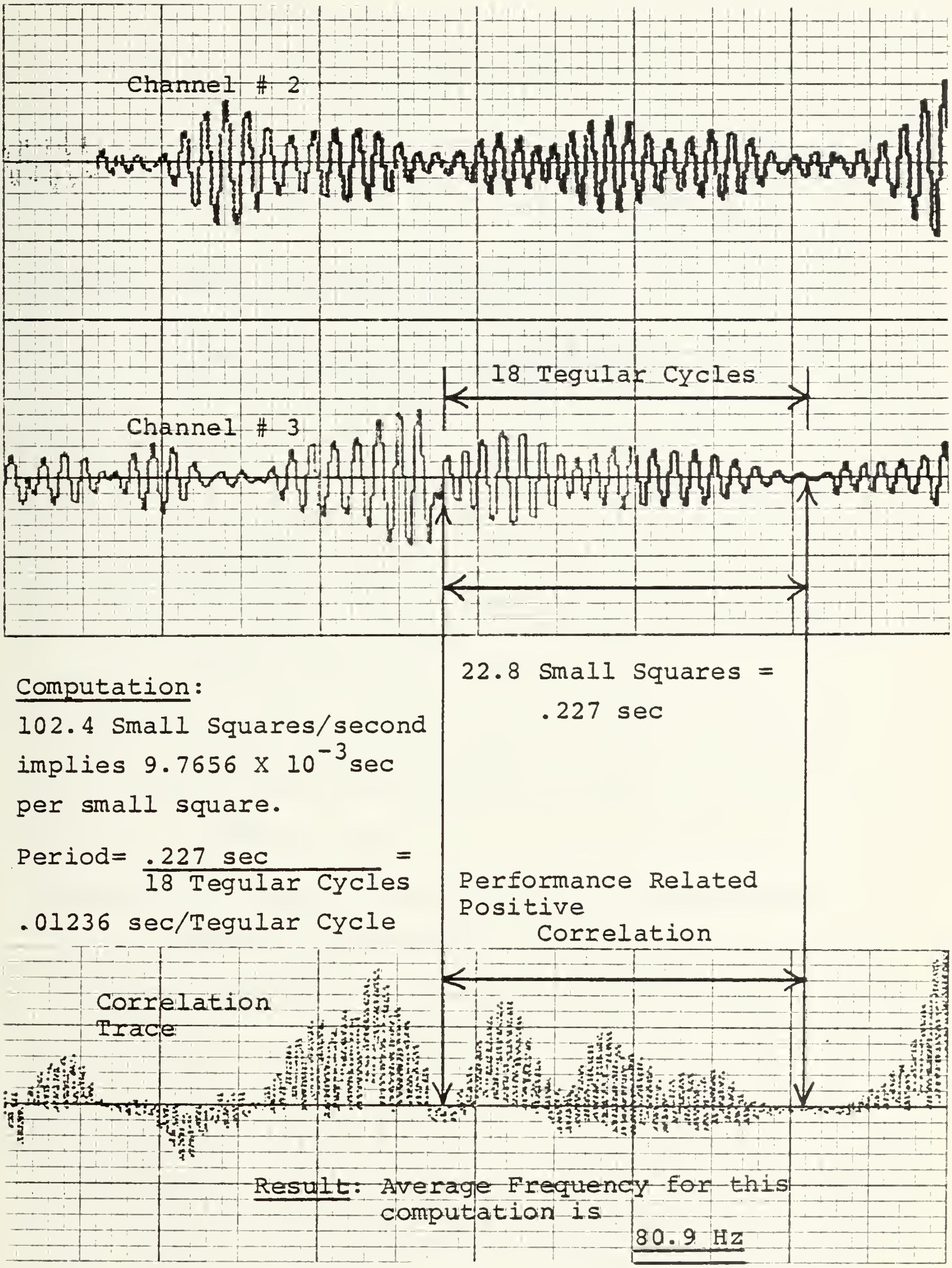


Figure 7-17. Sample calculation of Tegular frequency related to performance.

Sample Tegule Frequency Computations

TIME	CYCLES	FREQUENCY
.1826	14.5	79.6
.1719	14.0	81.4
.1865	15.5	83.1
.2930	22.0	75.1
.4200	35.0	83.3

TABLE 7-1

Note: The average value for the five frequencies listed in this sample is 80.5 Hz.

VIII. DISCUSSION AND CONCLUSIONS

A. DISCUSSION

Considerable skepticism is encountered in some circles when it is seriously proposed that significant measurable EEG phenomena occur above 20 Hz. There is a tendency to dismiss any higher frequency activity as myograms or some sort of basal muscle twitching. Where feedback is involved, critics suggest that the subject learns how to turn on the light through contraction of craio-facial muscles to "improve" his performance. These observations are valid to some extent when applied to data acquired under less than exacting circumstances.

The EEG project at the Naval Postgraduate School Bioengineering Laboratory has consistently identified higher frequency bands of interest as reported in Refs. 3, 7, and 17. The experimental configuration has been well planned and carefully constructed to ensure the minimization of noise and the acquisition of valid data at higher frequencies. Data indicating any possibility of myograms are disgarded. In short, every possible precaution, including screening the subject from highly unlikely extra-sensory perception (ESP) effects, is considered. An additional precaution against myogram effects is designed into the TWODET program. If the block of data used in processing the feedback information is saturated for any reason, including myograms, the block is zeroed and the feedback light is turned off as a result.

When one considers the complexity and enormous amounts of information processed for the execution of a simple movement such as deliberately standing up or writing this sentence, the idea of significant frequency components above 20 Hz begins to appear reasonable. As the complexity of the activity increases and time constraints are introduced, it becomes even more difficult to believe that the megabits of coded information being processed are limited to the low end of the EEG spectrum. There is very strong experimental evidence for the preferred frequency hypothesis and it is insulting to the brain to insist that nothing meaningful exists above 20 Hz in the brain electroencephalogram.

B. CONCLUSIONS AND RECOMMENDATIONS

It has been established that there are certain patterns of measured brain activity which represent the accomplishment of a specific task under carefully monitored conditions. These patterns occur at predictable preferred frequencies.

It is recommended that work continue in order to refine the results reported here. In addition, there are other areas of interest for investigation. These areas became evident because of the broadband nature of the HISCAN.EEG investigation. For example, a consistent and prevalent pattern occurs at about 155 Hz. This and other precise frequency patterns must represent meaningful signatures of certain types of brain activity.

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